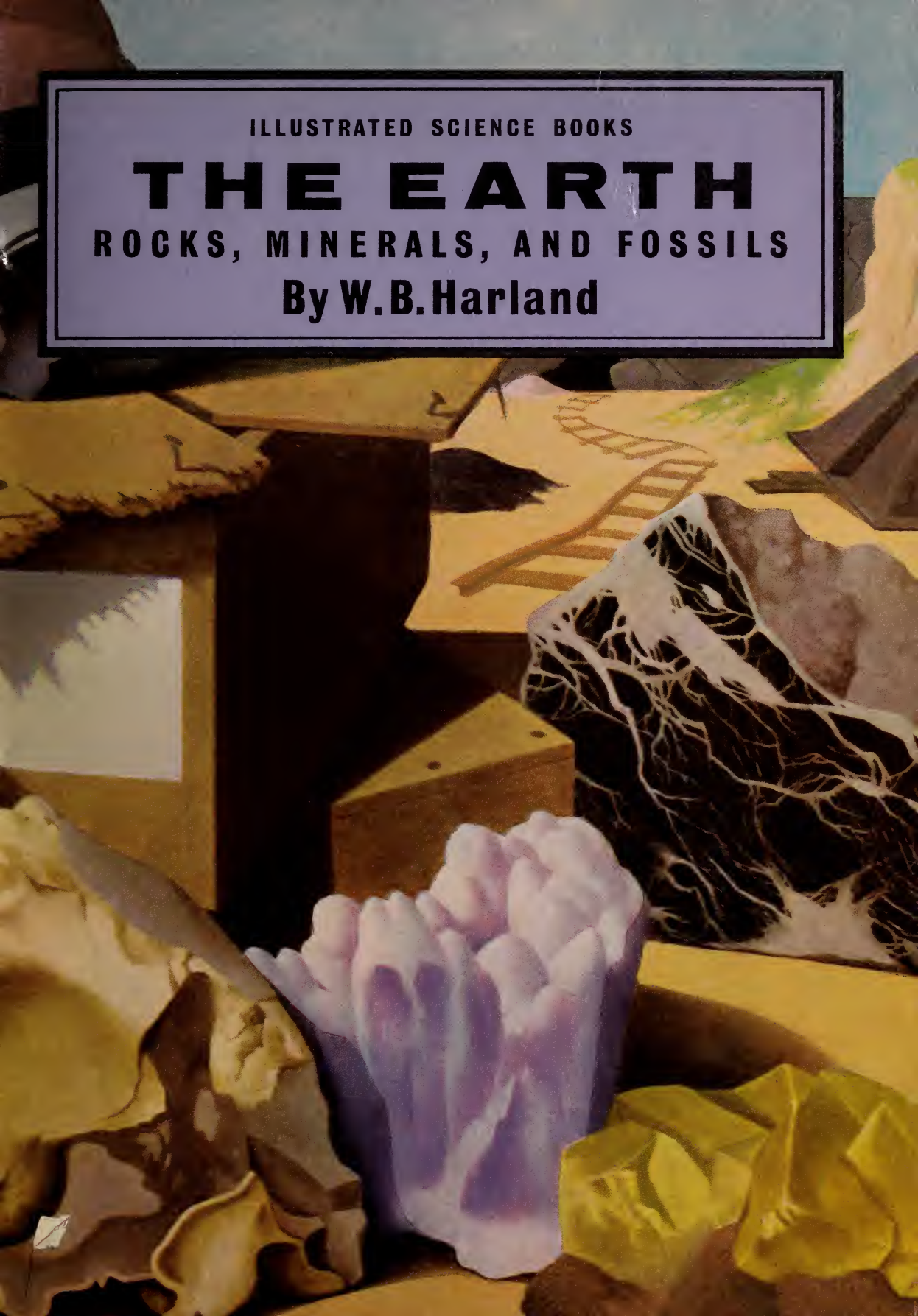
ILLUSTRATED SCIENCE BOOKS
THE EARTH
ROCKS, MINERALS, AND FOSSILS
By W.B.Harland

$4.95

# THE EARTH

## ROCKS, MINERALS, AND FOSSILS

How often do we pause and ponder the nature of our earth; what is it actually made of and how it has come about? W. B. Harland describes the structure of the earth. He interprets the various theories about the origin of the continents and the Ice Ages.

He explains the nature of the enormous variety of rock substances which go to make up the crust of the earth, from common sandstone to rare diamonds and precious gems, and he describes the evolution of all kinds of animal life, paying special attention to fossil remains.

There are useful chapters in which the amateur geologist is given the basic rules of rock-collecting and study.

Paxton Chadwick, noted book-illustrator, provides illustrations that combine the practical function of amplifying the author's text with helpful and explanatory diagrams and presenting artistically magnificent illustrations of the beauties of man's natural surroundings.

JACKET DESIGN: detail from an oil painting by TRISTRAM HILLIER

(*See back flap*)

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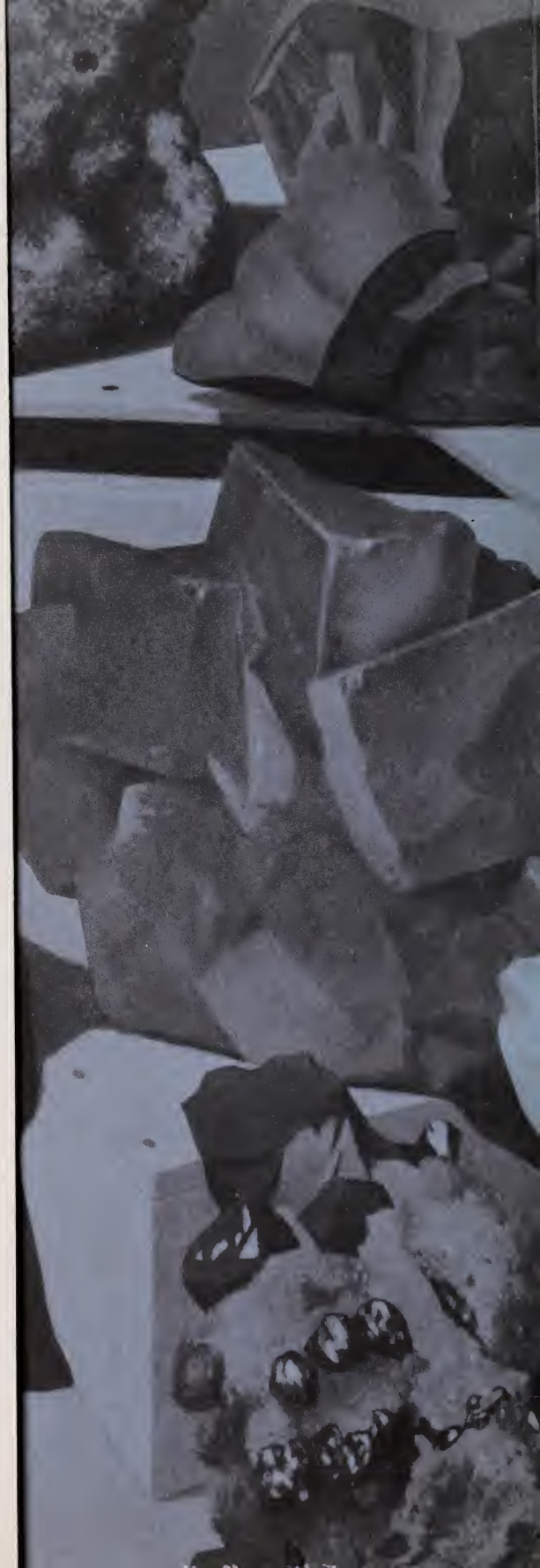

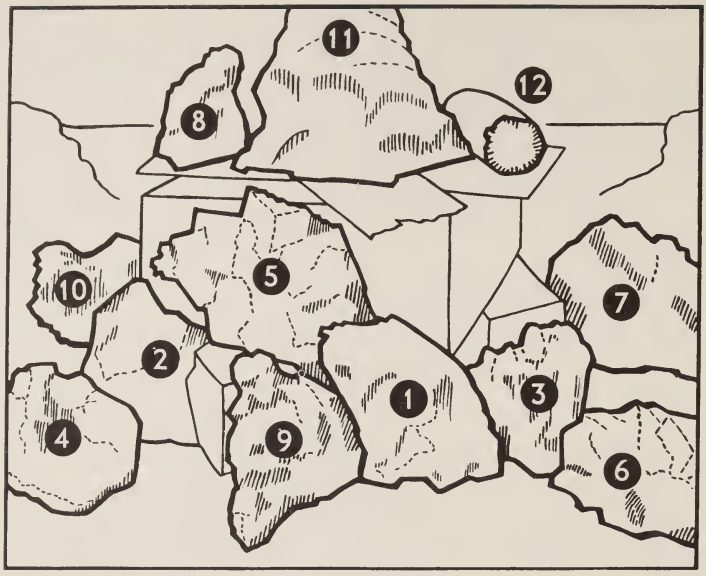


## THE ENDPAPER

1 Flint

2 Jet

3 Amethyst

4 Potato-stones

5 and 6 Fluorspar

7 Serpentine

8 Cassiterite or tin-stone

9 and 10 Galena

11 Kidney ore

12 "Thunderbolts"

$3 —

ILLUSTRATED SCIENCE BOOKS

# THE EARTH

ROCKS, MINERALS, AND FOSSILS

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## ROCKS, MINERALS, AND FOSSILS

Written by W. B. Harland

Pictures by Paxton Chadwick

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illustrated science books

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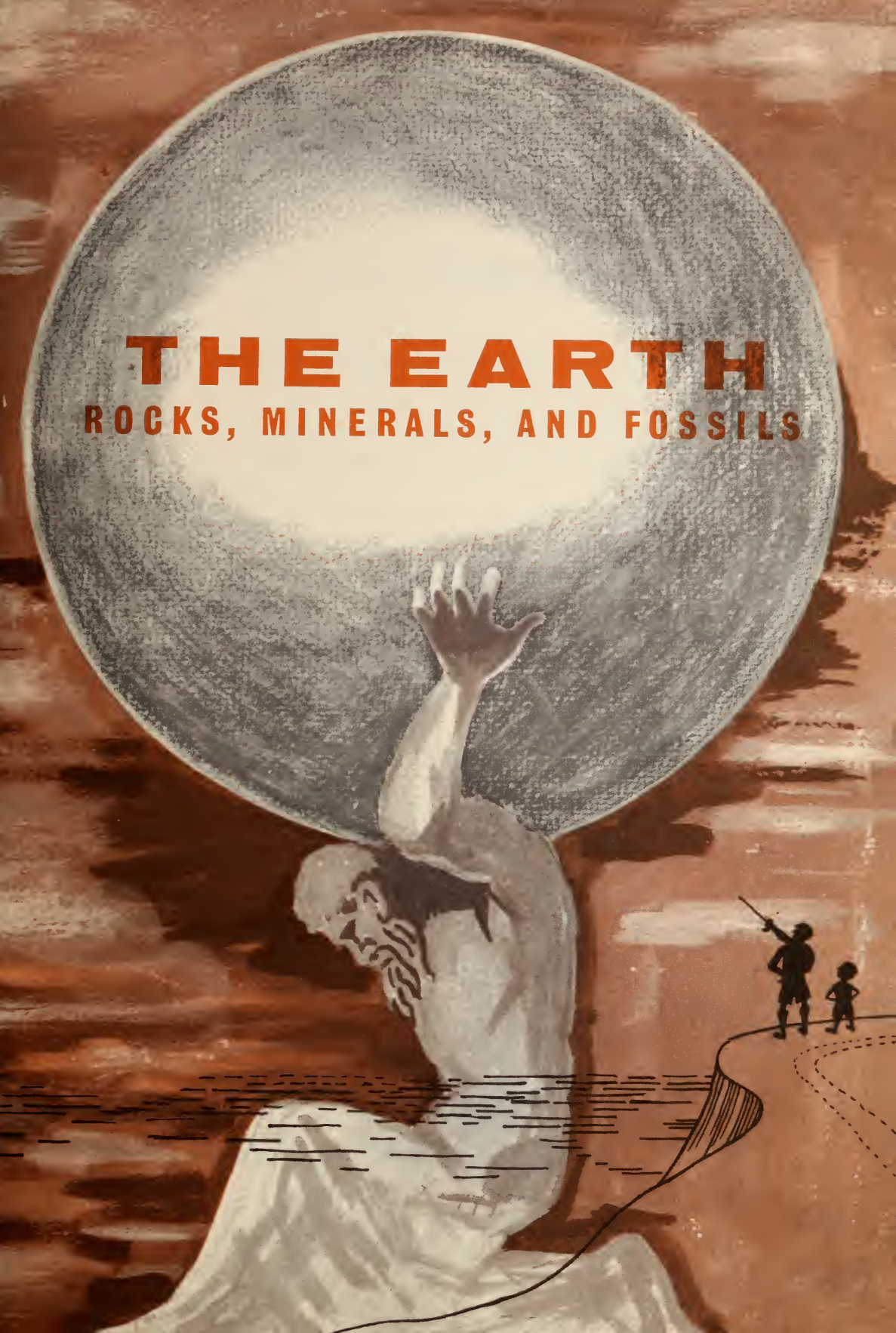
THE EARTH
ROCKS, MINERALS, AND FOSSILS

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# About the author and artist

## W. B. Harland M.A.

W. B. Harland was born in 1917 and became interested in geology when still a child. He studied at Cambridge before the war and returned to teach there in 1946; he is now University Lecturer in Geology and a Fellow of Gonville and Caius College. He is particularly interested in the geology of the Arctic and has organized and led many expeditions to Spitsbergen. He was for some time Associate Professor of Geology at the West China Union University at Chengtu in China. He is the author of a number of scientific papers. He is a member of the Society of Friends and is married, with a family of four children.

## Paxton Chadwick F.S.I.A.

Paxton Chadwick combines great talent as an artist, designer and illustrator with a life-long interest in natural history. As an artist he has had wide experience in various fields, designing posters and textiles and drawing cartoons as well as specializing in book illustration. His bias towards natural history has resulted in his illustrations for books on subjects like wild flowers, pond life, British butterflies and amphibians, among which are several which have been chosen to form part of the National Book League's Exhibition of the hundred best books of the year. *Animals of the British Isles*, which Mr Chadwick illustrated, was among the fifty British books at the fifth International Exhibition of Book Design. Mr Chadwick is married and has one son.

The publishers and author are grateful to Dr Fletcher Watson, Professor at Harvard University, School of Education for his kind help in the preparation of this book.

# About this book

This book is about the earth, especially what is known about it from the study of rocks, minerals and fossils. It is thus an introduction to geology or the science of the earth.

It is in five parts, the first of which attempts to show what geology was about and what problems now challenge us.

Part Two gives some of the ideas about the way the earth is made from its inner structure to its outer skin, and what is going on. This is a study of the earth as it is now.

Part Three looks at the earth's past history from the beginnings of the planet to the beginnings of life, and introduces historical geology. This is the story of the earth which must be pieced together from fragments of evidence found in the rocks.

Part Four is written from the view-point of man as an inhabitant of the earth. The resources of the earth are rich but limited, infinite in their variety and wonder, as man's changing needs discover.

Part Five is the most practical part of the book and tells how you can make the kind of observation on which the science of geology is built. If you can get into the field and collect and observe you will know the thrill of checking for yourself what you read in books.

The main purpose of this book is to stimulate and encourage an amateur interest in rocks, minerals and fossils, and to give some tips on how to go about a useful study of them. This could lead to important finds and research, for geology is a subject in which the amateur can still share in the fun of scientific discovery. There is so much to find out and geologists are too few to solve even all the obvious problems.

But if you don't take your hammer too seriously it is a good thing to know something about the countryside and the material resources of the world. With this knowledge you can enjoy what you see and be a more useful citizen. For many people the study of geology leads on to other sciences and there is no better starting point than this to lead on to chemistry, physics and biology, and no better conclusion than to bring these other

sciences back to bear on the complex history and structure of the earth.

You will want to look at the pictures first and so get some idea of what the book is about. The captions to the illustrations help you to do this without at first reading the text. By using the index at the back you can find where some part of the text is illustrated or where the subject of some picture is discussed, or you can simply use it as a reference book, and using the index and glossary find your way to the part of the book you want.

NOTE: Entries in SMALL CAPITALS indicate that they appear in the glossary

# *Part 1*

# INTRODUCTION

## 1. The story of discovery

From earliest days imaginative people have wondered at the marvels of the earth as well as at the heavens. The mystery of creation inspired some of the finest passages in the Bible. The early Chinese recorded details of earthquakes and discovered the LODESTONE or rock magnet. The Greeks, by watching the shadow made on the moon during an eclipse, discovered that the Earth was round and by simple observations deduced its approximate size. In western Europe in the Middle Ages minerals or peculiar stones began to be valued, especially those whose shape suggested some living thing, but though a great deal was written about FOSSILS at that time there was no clear idea of what they were.

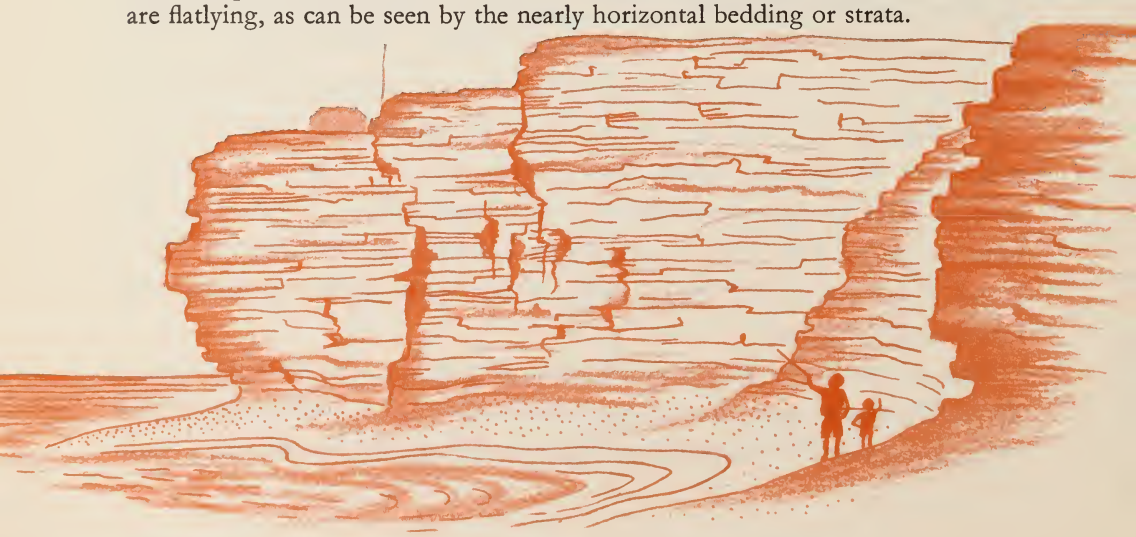
Towards the end of the eighteenth century a modern scientific approach to the study of ROCKS, MINERALS and fossils had emerged, and GEOLOGY became a recognized science. Men began to use their eyes and to write down what they saw, trying to account for these things only in accordance with real experience. This is a commonplace of science today, but at that time it was a stimulating release from accepted authority and uncontrolled speculation. The new criterion was what a man could actually see for himself in the rocks, minerals and fossils, rather than what earlier scholars had written about them.

One of the early giants of this revolution was JAMES HUTTON, a Scottish farmer who in the course of his many travels noticed that rocks appeared to be formed in layers, as though laid down one on top

of the other over a long period. He interpreted these layers correctly as ancient deposits of SEDIMENTS built up from material carried down by rivers, or broken off from the seashore by waves. These SEDIMENTARY rocks tell a story – a violent one, too, at times – of formation followed by TILTING, FOLDING, FRACTURING, change and eventual breakdown. Hutton found places where such BEDDED rocks, steeply inclined, were covered by other rocks sloping more gently in a different direction and resting on the worn surface of the up-ended older rocks. This type of structure, now called an UNCONFORMITY, Hutton interpreted correctly for the first time as evidence of a great gap in the record of earth history—an interval during which the earlier rocks were folded, uplifted and worn down. Finally, when they had subsided beneath the sea, a new set of rocks was formed above them. These in turn may have been subjected to movement followed by disintegration.

It was clear to Hutton that in these small exposures of rock beside the sea he had found the key to much of the earth's history. He marveled at its grandeur and at the immense periods of time which must have been necessary for such changes to be accomplished. He was one of the first to realize that large valleys had not always been there, but had been formed through the ages by the slow downward and

The cliffs pictured below were undercut by the sea. The exposed sedimentary rocks are flatlying, as can be seen by the nearly horizontal bedding or strata.



Sketch of sea cliffs exposing an unconformity. The steeply dipping rocks were sediments upended during folding and then eroded to a horizontal surface. The flat-lying sediments were deposited on top, and the unconformity is the surface between these two groups of rocks.

sideways cutting of the streams, and that they were the result of a process of wearing away, or EROSION, which could well be a source of all the bedded sedimentary rocks.

Hutton noticed, too, that within the sedimentary rocks there sometimes occurred large masses of GRANITE, a rock of unknown origin which some thought to be water-formed. "Fingers" of granite appeared to spread into the surrounding rock from the main mass, suggesting that the granite had once been a fluid and had penetrated the rock before solidifying. Since the granite must have been very hot to be fluid, Hutton suggested that it was formed from molten rock.

While Hutton was making these discoveries there had been much argument in France, Germany and Italy about the origin of BASALTS now known to be solidified LAVA flows. Some thought they were another kind of sedimentary rock deposited in water, but others with Hutton showed repeatedly how similar these rocks were to the solidified lavas known from recent VOLCANOES. All this suggested a widespread occurrence of IGNEOUS ("fire-formed") rocks, formed as intrusions within the rocks, or, alternatively as extensive volcanic lavas on the surface.

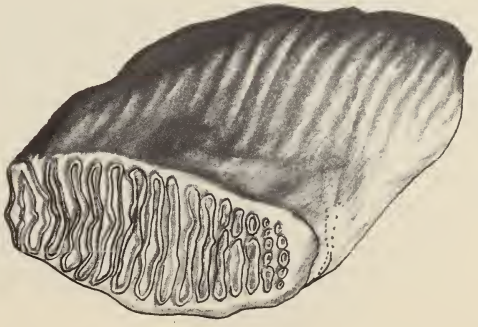
Part of the edge of a granite intrusion shows the (speckled) granite in veins penetrating the (dark) COUNTRY ROCK, from which some lumps have been entirely separated (xenoliths). Although the granite is now hard, one can imagine that it came into place as a hot liquid (magma) and then solidified while melting its way into the older rock. The illustration is of an area about a yard square.

By about 1800 the importance of both the igneous and sedimentary rocks was realized. As Hutton's writings were not widely read it was left to CHARLES LYELL some years later to explain these ideas more fully and to add many observations of his own. Lyell was a great traveler and writer, and he contributed perhaps more than any other man to establishing geology as a science in the popular mind as well as in academic circles. He considered that the processes and changes still taking place in modern times were sufficient to account for the FORMATION, DEFORMATION, and destruction of rocks in the past.

At first this idea was strongly opposed, and many eminent geologists at the time preferred to interpret unconformities and other changes in the record of the rocks as the result of catastrophic floods or cataclysms greater than anything known today. From factual evidence, however, Lyell argued that such explanations were unnecessary, and that all geological changes could have been brought about by ordinary processes of slow erosion and DEPOSITION, assisted by slight variations of sea level and gradual earth movements. It is interesting to find that during this early controversy CHARLES DARWIN was a

close friend of Lyell and stoutly defended his views. Lyell's *Principles of Geology* was published in 1830–2, and the ideas in it must have set Darwin thinking about the immensity of time needed for slow changes to bring about the wonders of creation. Darwin's *Origin of Species*, published in 1859, depended a great deal on the evidence provided by fossils.

Until about 1800 very few men had realized that fossils represented dead animals and plants preserved in various ways in the rocks. Leonardo da Vinci was one of these few, but his ideas were never followed up and it was L. C. F. D. Cuvier of Paris who did the first systematic work in the study of fossils. At that time fossil-collecting was a popular diversion and it was fashionable to display these curious objects in a drawing-room cabinet. In the country around Paris, where fossils are very numerous, Cuvier set about a thorough study of the subject, just as earlier naturalists had described and compared different species of animals and plants. He soon made some exciting discoveries, and he was the first to show that fossils often represent animals and plants quite different from anything alive today. It was obvious to any collector that many fossils were quite different from known living creatures, but in those days so much of the world was unknown that it was expected they might yet be discovered living in remote corners of the globe. However, Cuvier assembled skeletons from bones he had discovered, and reconstructed the forms of some of the larger monsters – in particular the elephants, whose bones evidently belonged to beasts quite different from our modern elephants. In short, it soon be-



The tooth of the extinct mammoth (or other elephant) is a common fossil, being very tough and liable to be separated from the skeleton and deposited with boulders of the same size. The tooth is seen to have an efficient grinding surface due to the folded layers of very hard enamel, which stand up as ridges.

came clear that most of the known fossils were remains of extinct life.

Both Cuvier in France and WILLIAM SMITH in England made another very valuable discovery. They noticed that certain beds of rock always contained the same fossils, and that these beds with their own peculiar fossils were always found in the same sequence. This led to one of the great advances in geology – the use of fossils to identify rocks formed in different places at the same time. Smith was able to astonish some of his friends by telling them where the fossils in their mineral cabinets had come from, showing that fossils were not only of interest but also of practical use. Nowadays many thousands of scientists, working for oil companies or on geological surveys, are applying the discoveries of Cuvier and Smith by making use of fossils in just this way.

Although fossils were used successfully for distinguishing the different bedded rocks, Cuvier believed that each layer of rock represented a distinct chapter in the history of the earth, each chapter being followed by some great catastrophe which led to the extinction of a

Fossil frond of a fern. It was preserved in a bedded rock formed in the Carboniferous Period (about 250 million years ago) and split open by a geologist's hammer or coal miner's pick. The vegetable matter has altered to a thin black film, and the delicate structure is preserved as an impression in the hard enclosing rock.

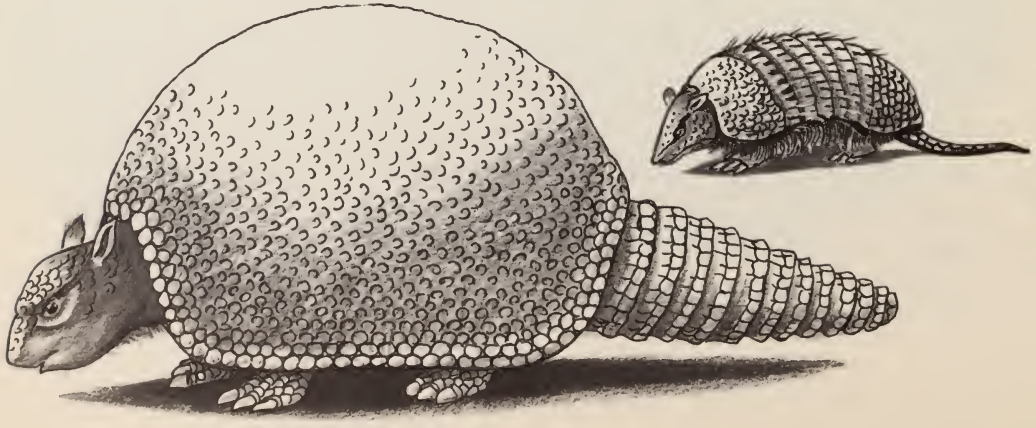
*Megatherium* – an extinct giant ground sloth – reconstructed from fossil bones. It lived from Miocene to Pleistocene times, during the last 20 million years, in North and South America. Some grew beyond the size of an elephant. A modern tree-sloth is shown for comparison.

particular group of animals, a new creation taking its place. This idea of successive creations of life, to correspond with the fossilized remains in the sequence of rock layers, persisted for many years. For instance Lyell, who otherwise maintained that the shaping of the earth was due to uniformly continuous processes, accepted at first this view of sudden changes in the composition of life, since its fossil record generally suggests this.

Darwin, on the other hand, thought that it could be better interpreted as a fragmentary record of gradual changes in the succession of life on the earth. To account for the difficulty that each new group of fossils seemed to be very different from the previous one he supposed that sedimentary rocks represented just a small and very incomplete part of the geological record. He thought that while many millions of years must have been necessary for slow changes of life to take place, only a few of the living creatures of each period would become fossilized, and only a small proportion of the rocks themselves would be preserved. Darwin gathered together an enormous amount of evidence to support his ideas, and put forward his theory of EVOLUTION by NATURAL SELECTION to account for the slow changes which he deduced must have taken place. In difficult conditions and in times of severe competition, the less well-adapted of a number of offspring would not survive, while their more fortunate brothers and sisters would be spared (though the latter's own offspring would be subject to the same selective process). So a slow change in population may have become possible simply because of the difficulties and dangers of life. Evolution is now a generally accepted theory, but it is still not fully understood. The collecting of fossils provides many a clue or missing link.

When Lyell was still arguing his view, which has come to be known as UNIFORMITARIANISM, and when Cuvier was unearthing

*Glyptodon* – reconstructed from fossils found in South America from the Pliocene Period, during the last 10 million years. The smaller modern armadillo belongs to the same mammalian group (edentates) so characteristic of South America, and may well have stimulated Darwin's earliest thoughts on evolution.



This impression of rugged mountain country shows a typical valley glacier with tributary glaciers. Rock débris falls off the cliffs onto the ice (lateral moraines) and when two tributaries join they continue in the middle of the ice (medial moraine). The peaks are carved by freezing and thawing of water at the head of the glaciers.

fossil animals near Paris, Louis Agassiz was beginning to study the effects of valley GLACIERS in the Swiss mountains. He noticed how large blocks of rock in the high mountains would fall on the ice and be slowly carried down the glacier. When the ice melted lower down the valley the rocks were left behind, forming what is called a MORAINE. Having seen this in many places near the glaciers, Agassiz began to realize that there were similar boulder DEPOSITS in places far removed from present-day ice. It seemed to him that in the past the ice must have extended much further than it does today. Over much of England and parts of Europe there are widespread deposits of clay with boulders, then thought to be the remains of the great Flood described in the Bible. On going to England Agassiz was able to convince Lyell of the glacial origin of these deposits. Lyell was only too glad to dispense with the idea of a sudden catastrophic flood unlike anything known today, and to replace it in his system of geology by the idea of a slow advance and retreat of glaciers. Later Agassiz went to America and was delighted immediately to find further examples of ice-polished rocks and boulder clays already so familiar to him. In due course he discovered these traces of ice action over a large part of northern North America. Such widespread evidence of glaciation in

In the distance are a lake or sea in the floor of a glaciated valley and a rugged skyline typical of glaciated country. In the foreground are large boulders, gravel and clay transported by moving ice and then left where it melted.

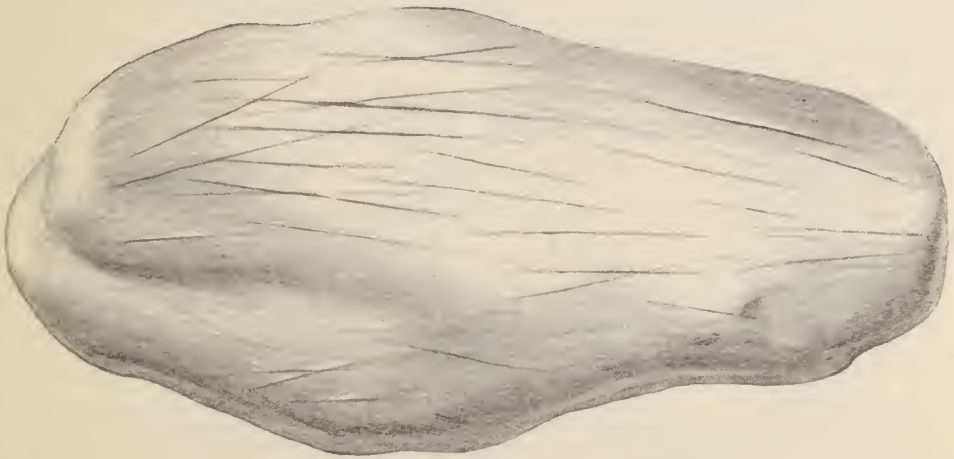
the northern hemisphere finally established the historical fact of the last ICE AGE.

In America by the middle of the nineteenth century much was known about the Appalachian Mountains. This great range is made up of folded sedimentary rocks. Many examples are now known of such FOLD MOUNTAINS all over the world, but the Appalachians, together with the European Alps, are among the most famous geologically. JAMES HALL was struck by the remarkable thickness of the deposits making up the folded structures, and by the fact that the fold mountains seemed to be formed just where the rocks were at their thickest. He noticed, too, that rocks of the same age could be traced to the west, where they became thinner. The sedimentary layers of which the fold mountains were formed were thicker than the continuation of the same layers to either side. It seemed to Hall that the formation of a great belt of thick sedimentary rocks might, of itself, collapse in folds. This idea was developed by JAMES D. DANA, who gave the name "GEOSYNCLINAL" to thick piles of sedimentary rocks of this kind. He suggested that wrinkling of the earth's crust, due to compression, formed a furrow in which the deposits were then laid down,

and that as compression continued the rocks of this geosyncline were folded. A SYNCLINE is simply a downfold, and geo- (to do with the earth) means it is a big one; indeed GEOSYNCLINES often contain beds or layers of rock deposited without much interruption, one on top of the other up to ten miles thick, and this means that their base must go deep into the earth's crust. Even more remarkable is the observation that fossils of animals that live in shallow water occur in the early as well as the late deposits formed in geosynclines. Apparently all the layers of these deposits must have been formed near sea level, and there must have been a steady subsidence of the order of ten miles to make room for the new deposits on top.

Only a few names have been mentioned in the story of discovery above, but during the nineteenth century there were many hundreds, even thousands, of geologists, including many amateurs, who were dedicated to the collecting of fossils and minerals, the mapping of rocks, and the accumulation of a great mass of information without which the more dramatic discoveries could not have been made.

A smoothed and striated boulder, transported by a glacier. The scratches are typical of boulders moved by ice and are formed when, held in the ice, they are scraped along the rock at the bottom of the valley. When the boulder has traveled many miles in this way it is known as a glacial erratic.



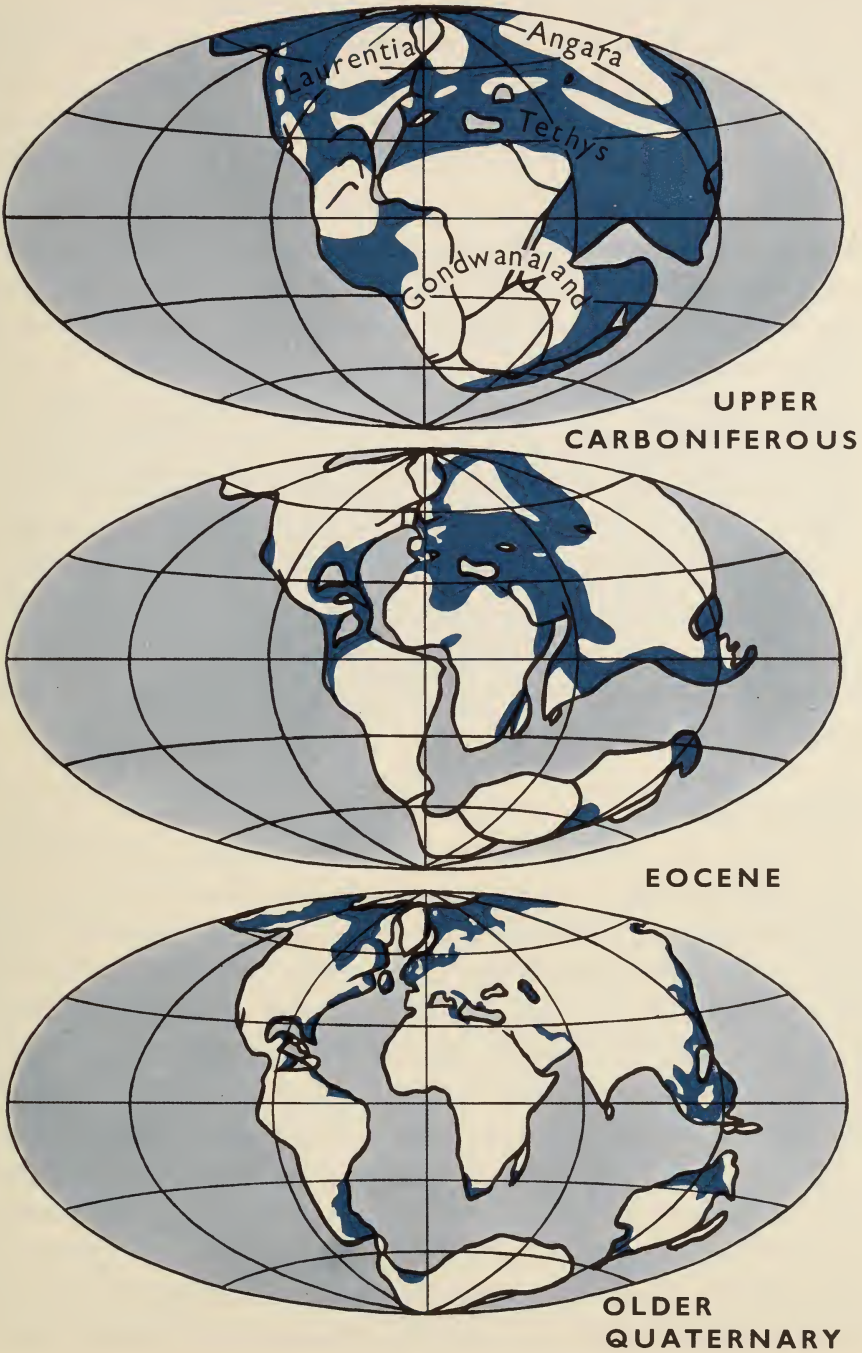
# 2. Some outstanding problems

Each major discovery in geology is the result of a great deal of discussion and argument over what was at the time a challenging problem. New problems have arisen as old ones have been solved, and today there are many questions on which there is as yet very little agreement but which, when solved, may rank with the earlier discoveries. For the progress of science is a continuing and exciting activity in which all can play their part.

*The origin of the earth*

The first and perhaps the biggest problem is how the world began. Up to the early part of the last century many people in the West accepted the biblical story of the Creation (calculated for the year 4004 B.C.) as told in Genesis. In more recent years there have been several alternative ideas about the origin of the SOLAR SYSTEM, of which the earth is a part, and these may be grouped into two types of theory, both of which presuppose some astronomical disturbance as yet undefined. The first type derives from the PLANETESIMAL HYPOTHESIS of THOMAS C. CHAMBERLIN and FOREST RAY MOULTON, which assumes that the planets have grown by the accumulation of solid particles. According to this view the planets were built up from a great collection of small bodies which came together very quickly at first and then began to heat up in the center when something the size of our present world had grown. We may regard this as a "cold earth" theory. The second type, a "hot earth" theory, assumes that incandescent gas cooled down and condensed into a series of molten

Maps illustrating Wegener's theory of continental drift, according to which the continents in Carboniferous times (say 300 million years ago) were closer together as in the top map. According to this theory they drifted apart – America from Europe to open up the Atlantic Ocean, and so on. Dark blue shades land then covered by sea.


Laurentia
Angara
Tethys
Gondwanaland
UPPER CARBONIFEROUS
EOCENE
OLDER QUATERNARY

balls or droplets, which became the PLANETS. Such a problem is difficult to settle by any direct evidence to be found on the surface of the earth, and requires the full attention of astronomers. It will be discussed further in Chapter 9.

*The origin of the continents*

The problem of the origin of the continents is another subject of much geological argument, and is also discussed in Chapter 9. One argument concerns the Theory of CONTINENTAL DRIFT which proposes that some continents at some time drifted apart and others possibly drifted together. The alternative view (the theory of PERMANENCE) is that they have always remained in approximately the same positions. Unfortunately much of the evidence available can be interpreted either way, but it seems likely that the next few years will settle this problem. With each passing year new information is obtained about this possible drift. Many who a few years ago would have claimed Continental Drift to be quite impossible are now beginning to change their minds. But even if the continents have drifted over the crust of the earth, the main questions remain as to just why, how, when, and where they moved.

*Ancient climates*

Related to this problem is the distribution of past climates. Even if the continents have not wandered, there is plenty of evidence that past climates have not been as they are today. For instance in the Arctic regions of Greenland and Spitsbergen there is evidence of coal forests having existed at intervals throughout much of the later history of the earth; and some other deposits were certainly formed in hot climates. On the other hand, in India, South Africa and Australia there are many signs of former glacial conditions. When much evidence of this sort is put together it suggests that if the continents have not wandered the poles have done so—that is to say, the positions of the North and South Poles and the Equator have been different at different times. Possibly a combination of both Continental Drift and POLAR WANDERING would be necessary to account for all the facts.

*Geosynclines and folding*

A fourth outstanding problem is one which Hall and Dana stated but left unsolved—how geosynclines are formed and deformed. If great thicknesses of deposits have all been formed in quite shallow water, then the question is whether that part of the earth's crust is subsiding gently and sedimentation is just keeping up with it, or whether

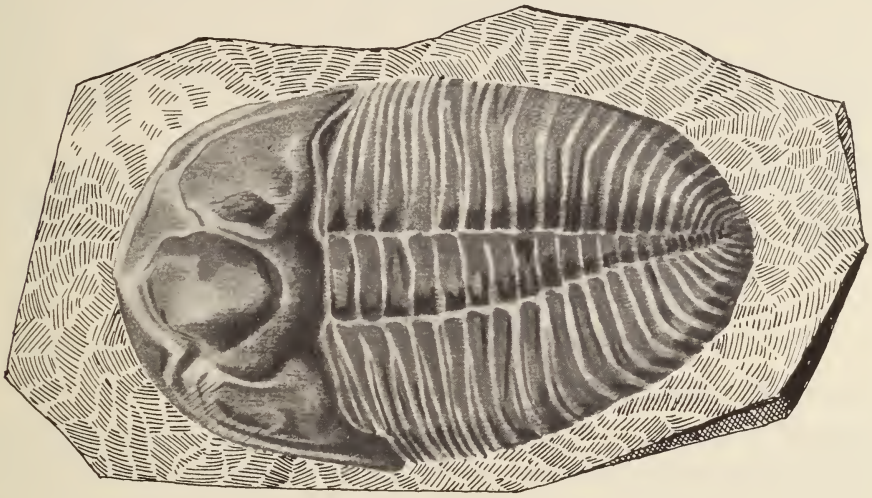
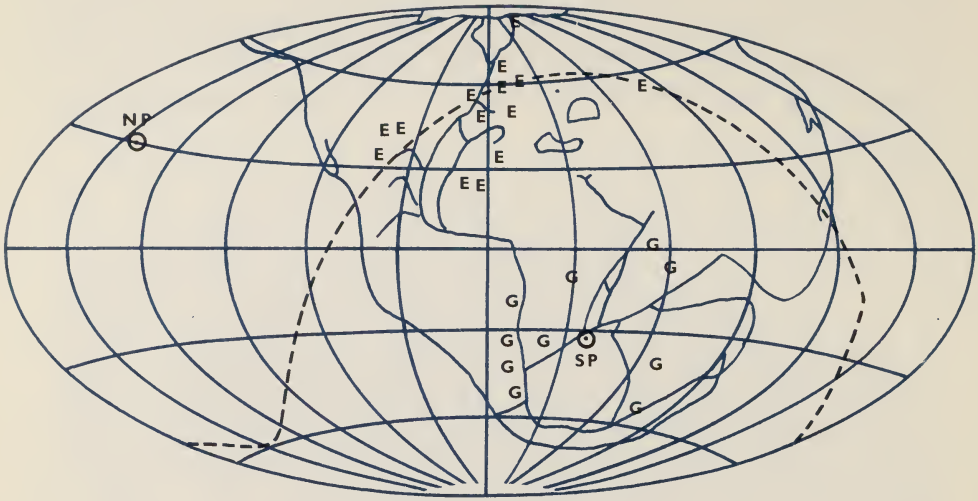


Illustration of a fossil trilobite seen from above in a slab of rock. This class of animal is now extinct, and flourished in Lower Paleozoic times (600 to 400 million years ago).

the subsidence is keeping up with the sedimentation – in other words, does the ground sink because a new layer of sedimentary rock is formed, or was the ground sinking in any case and the space then filled up by newly-formed sediments? Each of these possible solutions has its difficulties, but recently new light has been thrown on them. It is now thought that deep in the earth's crust there may be some delicate adjustment to changes of load at the surface—so delicate that even a few hundred feet of new sediments could cause considerable sinking, or on the other hand a little erosion at the tops of mountains could cause great uplift. But even if we can explain the vertical movements necessary to cause the geosynclines, we still have to account for




According to Wegener's reconstruction of the continents in late Paleozoic time the equator (dashed line) and poles (NP and SP) were drawn so as to include the various evidences of floating ice on glaciers (G) nearer the South Pole and evaporite (e.g. salt) deposits (E) nearer the Equator. This implies some wandering of the whole earth about the axis of spin, as well as of individual continents.

what is nearly always a catastrophic ending. At the final stage they are usually subjected to intense squeezing and folding. What causes this? Does it result from contraction of the whole of the earth, like the shrinking of an apple and the wrinkling of its skin; or could it be that continents have in fact wandered and in doing so folded up the geosynclines which happened to be in their way? Here again we have a series of related questions that are very difficult to answer.

*The origin of granites*

A further outstanding problem which has given rise to much controversy is the origin of granite. Early in the last century basalt was finally classified among the igneous rocks and for many years geolo-

gists assumed that granite was also an igneous rock. During the present century, however, it has become clear that some granites were not formed by the solidifying of molten rock, and are therefore not igneous. They are apparently caused by chemical changes altering the character of earlier sedimentary rocks, with some of the original material being lost and new material introduced. This process is harder to understand but has been well established in some cases, and geologists now have to decide in which of these two ways some of the important granite masses of the earth's CRUST have originated. Some believe that there is a granite layer under the surface of the earth's crust, or at least under the continental land masses, while others consider that granite is formed only in regions of mountain building; but it is not at all obvious where the granite-forming material comes from in the first place.

*The origin of life*

The most fascinating problem of all, and probably the hardest to solve, concerns the origin and early history of life itself. In many parts of the world the first recognizable fossils are 500–600 million years old. A great deal has already been discovered about the development of life from that time onwards, through the study of fossils preserved in rocks of various ages. But what was in existence before the earliest fossils appeared, and why life spread so suddenly, are questions considered further in Chapter 11 but still unanswered. If we accept the idea of evolution, which works so well as an explanation of the last 500 million years, it is probable that a series of changes of which we have no record preceded the earliest, or CAMBRIAN, fossils. These fossils are themselves highly organized and seem to be far removed from the simple origins of life. However, we know of rocks up to about 3,000 million years old – much older than the Cambrian – and this vast time would allow for the development of simpler forms of life up to the comparatively advanced forms found in the Cambrian period.

Some fossils of a sort, found in rocks as old as 2,000 or more million years, may possibly represent very primitive plant structures,

but nothing at all is yet known about the early stages of animal life. If something could be found to throw light on this mystery, it would indeed be an exciting discovery, but it might still leave us in the dark as to how life started in the first place.

Apart from the twin problems of the ultimate origin of the planet and of its inhabitants, both of which are beyond the power of the rocks alone to tell, the succeeding events on the surface of the earth, and possibly even deep down, may be gathered piece by piece and put together into a story of the earth and its life, all from the study of rocks, minerals and fossils.

# 3. Rocks, minerals and fossils

*Rocks*

The planet on which we live is about 8,000 miles in diameter, but it is only the outer ten miles of it that geologists know much about. This knowledge has been gained largely from the study of rocks, formed of the natural materials which make up the earth's outer layers. Some rocks are very old, some are not so old, but the materials of which they are made go back to the beginning of the world itself.

All rocks which have at some time been buried to a great depth are hard, like granite, SLATE or LIMESTONE. But many other materials also known to geologists as rock may be quite soft – for instance the sand on the seashore, the newly-formed deposits at the bottom of the sea, the deposits on river banks, and the soil which so often covers up the harder rock. Apart from air, water, animal and plant life, and all man-made objects, everything on or in the earth is probably rock. Whatever the earth may hold deep in its interior, if it were brought to the surface it would be some kind of rock.

Igneous rocks are those which were formed by the cooling and solidifying of lava at the surface of the earth, or of molten material deep down. Igneous rocks formed at the surface are known as VOLCANIC rocks – basalt is a common example of this type. Igneous rocks formed deep down in the earth in large masses are known as PLUTONIC rocks and a common example of this type, is intrusive granite. Basalt and granite between them form a large proportion of all igneous rocks.

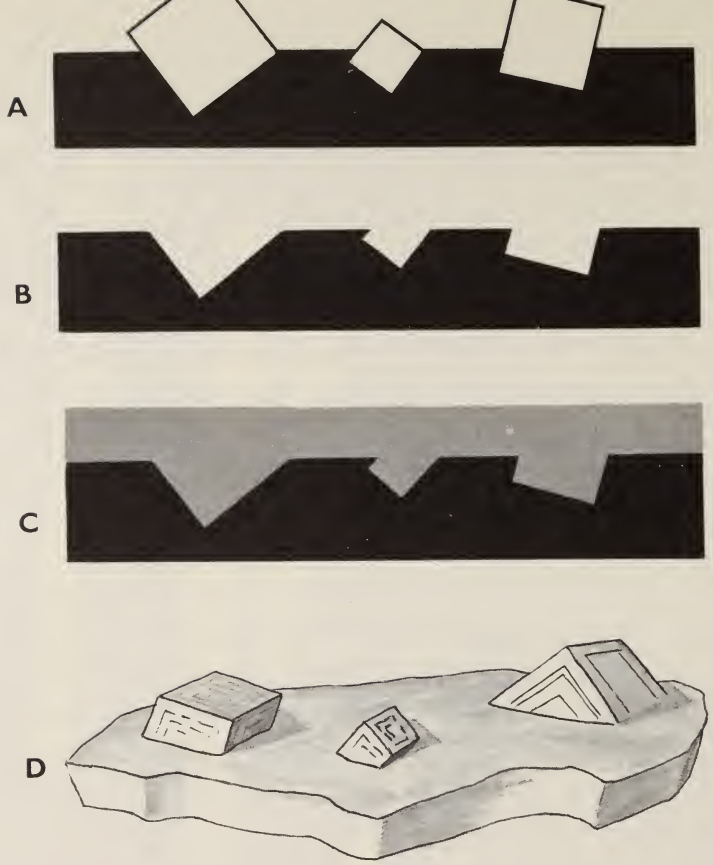
The sedimentary rocks were formed under ordinary surface conditions, either on land or beneath the sea, where temperatures were low and pressure not too high. The best-known rocks of this type were formed in the sea; for example SANDSTONES, limestones, and SHALES. Other sedimentary rocks include river and lake deposits,

sand dunes, beach shingle, soil, STALACTITES and STALAGMITES in caves, ROCK SALT, COAL, and many IRON ORES. Because of the many different conditions under which sedimentary rocks could be formed, they occur in much greater variety than the igneous rocks. Sedimentary rocks are usually known for their bedded or layered nature, because deposits were laid down gradually, accumulating layer upon layer. Sedimentary layers are called STRATA, and may often be seen in cliffs or quarries. They were laid down as flat beds, but when, as so often happens, they are seen to be folded or contorted, it can be assumed that earth movements have probably taken place.

There is yet a third group of rocks, the METAMORPHIC rocks. Metamorphosis is a word for change, and metamorphic rocks are simply rocks which have undergone great alteration since they were formed. All rocks undergo gradual changes, such as hardening, cementing, compacting and cracking, from the very moment of formation, but the term "metamorphic" is reserved for rocks which have been subjected to very severe changes by high temperatures, great pressures or strong movements. Sedimentary rocks under such severe conditions may be changed to metamorphic rocks, as for instance when a limestone is turned into a MARBLE, or when a shale is turned into a slate or MICA SCHIST. Often a complete transformation takes place and the rock is wholly recrystalized. Igneous rocks, too, may be changed in this way to form metamorphic rocks, and even metamorphic rocks themselves may be converted into other types of metamorphic rock.

Still greater heat may cause rocks to melt, and on cooling down they solidify as new igneous rock. Thus igneous rocks may have been formed from rock which was previously sedimentary, metamorphic, or even itself igneous. All kinds of rock are also subject to breaking and decay, and the fragments and products of decay travel down

Sea cave in Staffa, a Scottish island, formed of basalt. The structure is known as columnar jointing and is the result of contraction when a mass of basaltic lava was cooled uniformly above and beneath. The contracting lava was split by cracks or joints arranged with nearly perfect regularity.




The three diagrams show how cubic salt crystals were formed from evaporating salt water in the mud (A). After the mud hardened the salt crystals were dissolved by fresh water (B) and the cavities filled with the overlying sandstone moulded to the shape of the salt crystals (C). When these rocks are exposed today the mudstone is weathered away, leaving the salt pseudomorphs made of desert sandstone, seen upside down in D.

streams to the sea to form new sedimentary rocks in various places. Sedimentary rocks then, may be formed from the residues of igneous rocks, metamorphic rocks or earlier sedimentary rocks.

Matter itself seems indestructible, but in the course of the history of our world it has undergone many changes.

*Minerals*

Minerals are the particles or substances from which rocks are built. Some rocks are formed largely of one sort of mineral – limestone, for instance, may be formed almost entirely of CALCITE. Other rocks are a mixture of several minerals – for example, granite is made up of

QUARTZ, FELDSPAR, sometimes MICA, and other minerals as well. Minerals are of many kinds and each kind which has quite definite properties and composition is known as a mineral species. Although there are many hundreds of different minerals near the surface of the earth there are only about thirty common ones, and these form the greatest proportion of all the rocks.

Minerals are made up of one or more ELEMENTS. Most minerals are CRYSTALS in which the atoms are arranged in a particular pattern or network. In this network each ATOM always has the same relationship to the other atoms, and the pattern repeats itself – like the pattern on wallpaper – on a very small scale, so that there is always the same proportion of one kind of atom to another kind. The particular network of atoms gives each mineral crystal its peculiar properties. Quartz, for example, consists of innumerable atoms of SILICON and OXYGEN, built up together in the proportion of one to two, so that the chemical formula is $SiO_2$, meaning one atom of silicon and two of oxygen. This does not mean that there is a separate MOLECULE of silicon dioxide; for in quartz there is a continuous structure, like a climbing frame, in which each atom of silicon connects with four of oxygen, and these oxygen atoms connect with other silicon atoms. The whole structure is very complex, but the proportion is always exactly two to one. These together give quartz its individual characteristics: it is just a little harder than steel, it does not break in smooth flat surfaces, it grows in TRIGONAL crystals, and it bends light in a very definite way. Minerals have definite composition and definite properties, but rocks differ from one to another because they are formed of various minerals in varying proportions. In addition to its scientific use, as above, the word "mineral" is used in a different sense referring to minerals and rocks, especially when of economic value.

*Fossils*

Fossils are the relics of animals and plants preserved in rock. Because life requires relatively low temperatures near the earth's surface or in the sea, fossils are found only in sedimentary rocks. It is inconceivable that any living thing could survive within the molten lava which eventually became igneous rock. It is also rare for fossils,

once formed, to survive the severe changes which created the metamorphic rocks. So in general it can be assumed that fossils are peculiar to sedimentary rocks.

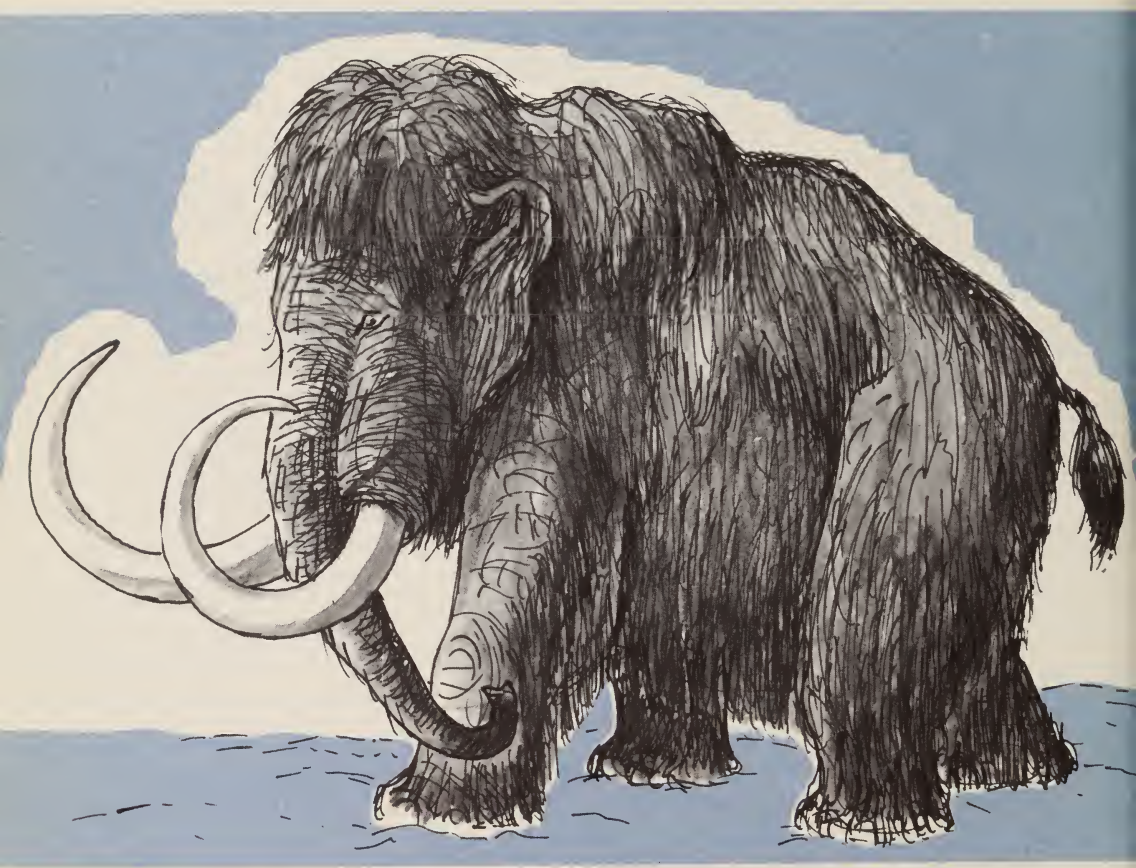
After the death of an animal the soft parts are usually eaten or decay very rapidly, leaving only the hard parts, or SKELETON. By skeleton we mean the bones of vertebrate animals, the shells of shellfish, the hard outer covering of crabs and lobsters, and the woody tissues of plants and their resistant pollen and spore cases. Very occasionally the whole of a body has been preserved – as for instance when some MAMMOTHS fell into a bog during the Ice Age. Their bodies were frozen and remained frozen until quite recently, when they were excavated in the Soviet Union: they are now preserved there. Dogs were able to eat the meat. This was obviously an exceptional case of refrigeration. There are other unusual ways in which bodies may be preserved, as in PEAT, in highly saline rocks, or in PITCH, but normally fossils are simply skeletons, usually altered.

Preservation of such skeletons can only happen when newly-forming sediment covers them up quickly so that they escape destruction on the surface of the earth. Once entombed in the rock the original material may be preserved for a very long time, or chemical changes may replace the original material with new mineral matter. Tree trunks, for instance, are sometimes replaced by SILICA, and the CALCIUM CARBONATE mineral (ARAGONITE) of snail shells is usually recrystalized into another form known as calcite.

Sometimes these chemical changes take place on such a small scale that even minute structures are preserved, while in other cases only the outer parts remain. Quite often the original fossil has been completely removed, leaving only its cast or impression in the rock. So the student of fossils has to reconstruct the shape, structure, and habits of bygone living things from their skeletons or casts.

The Grand Canyon, Arizona. The flatlying sedimentary rocks represent many geological systems (Cambrian to Triassic), resting on more ancient Precambrian rocks exposed at the bottom of the Canyon. Hundreds of millions of years without tilting are represented before the present erosion in arid conditions which led to the characteristic precipitous cliffs.

Sometimes evidence of past life is found as TRACE-FOSSILS or marks left by the original creatures. Footprints, for example, have been found in many rocks, but it is not always certain what kind of animals trod there. Scientists have found evidence of worm tubes but can only guess at the species which occupied them. Sometimes there are traces of eating habits – perhaps the grazing of shell fish on the vegetable slime covering rock surfaces, or a pattern of burrowing through a mud surface. In such ways as these it is possible to reconstruct the presence and habits of living things in past times.



Mammoth. This is a reconstruction of an extinct member of the elephant family which was living as recently as the last ice age. It is well known, not only from fossil bones and teeth (see page 13), but also from complete carcasses preserved in frozen mud. A more accurate representation is possible than is usual when reconstructing the living appearance from fossils.

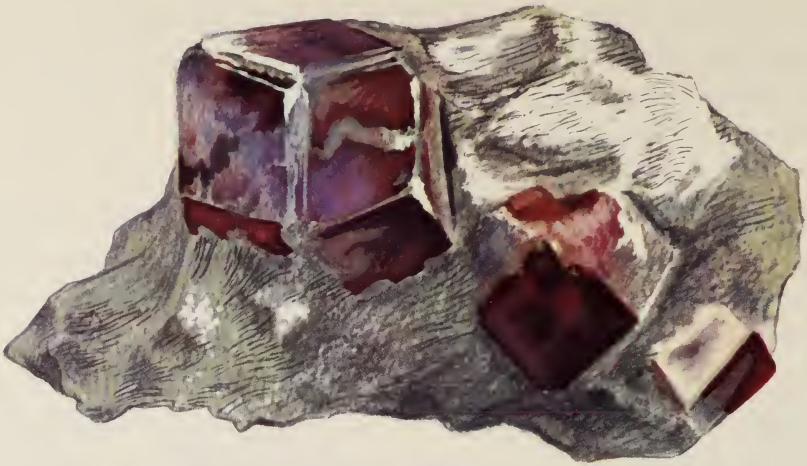
Fossils, like minerals, are of quite definite kinds, so we may talk of animal and plant SPECIES. The variation within each species often makes identification difficult.

*The earth sciences*

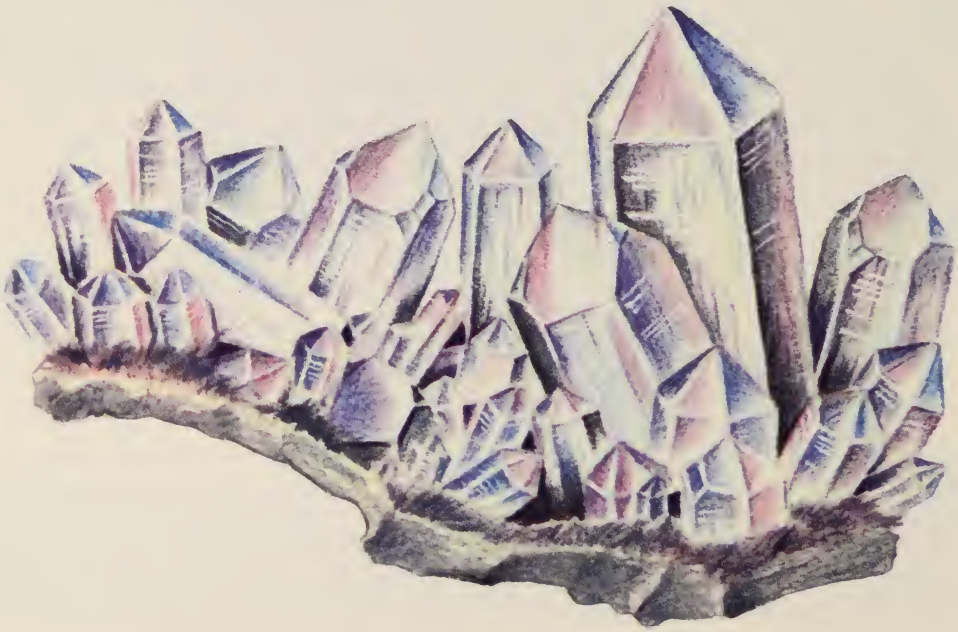
The study of rocks is known as PETROLOGY; of minerals, MINERALOGY; of fossils, PALEONTOLOGY. Each of these three sciences may be pursued for its own sake, but no branch of science can really be studied in isolation or stand by itself. The world is a whole, and the different sciences are simply different aspects or ways of looking at it. Petrology, mineralogy and paleontology come together under the wider heading of geology, the study of the nature and the history of the earth. The distinguishing feature of geologists is an ultimate interest in earth history, and rocks, minerals and fossils are the clues in its unraveling. But the same materials are of interest to other scientists for different reasons. As will be seen from Chart One, the science of geology is closely connected with the various sciences of physics, chemistry and biology. For instance, STRATIGRAPHY, which deals mainly with the layered rock, often needs the fossil evidence of paleontology to establish the rock strata in order of age.

Paleontology in its turn leads on to the study of living animals and plants – zoology and botany – while petrology moves inevitably on from the study of rocks to mineralogy and then to chemistry itself. And since rocks are contorted, folded and broken under great pressures, the petrologist soon finds himself involved in the study of STRUCTURAL GEOLOGY, which in turn may require the use of the elaborate methods of GEOPHYSICS to examine the structure of the earth's crust and what lies beneath it. The study of rocks provides evidence not only of great upheavals but also of the past distribution of land and water, deserts, forests, swamps, ice ages, deep seas and high mountains – all of which borders on PHYSIOGRAPHY, itself a branch of physical geology and geography.

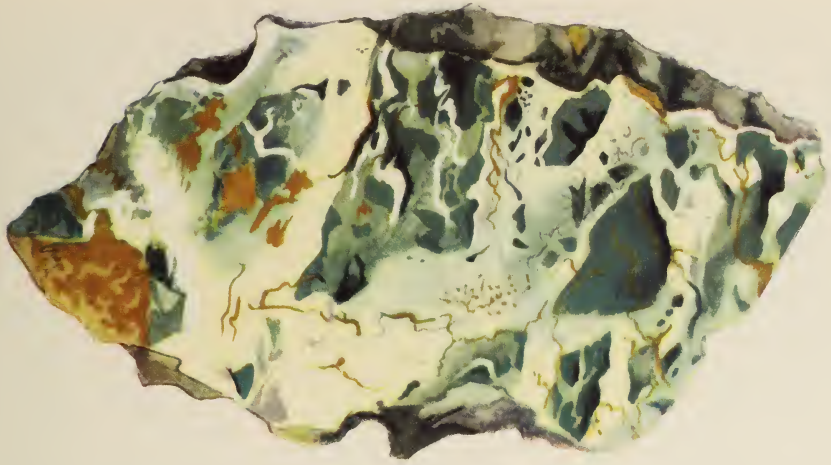
Geology, the subject of this book, is a comprehensive science based on the evidence of rocks, minerals and fossils but drawing also on other related sciences to throw light on its many difficult problems.



Specimen of garnet mica schist. This is a metamorphic rock formed under very high pressure from mudstones or shales. Garnet, seen as very large crystals in this specimen, is typical of high pressures and is thus a useful mineral for interpreting the conditions of rock formation.



Quartz crystals. These finely developed crystals were formed slowly from solutions of silica in water at relatively low temperatures in a crack or cavity in the rock. The distinctive color is due to a trace of manganese and gives the variety of quartz known as amethyst. Quartz usually shows a six-sided symmetry, but some of the crystals here reveal a more subtle left-and right-handed threefold symmetry.



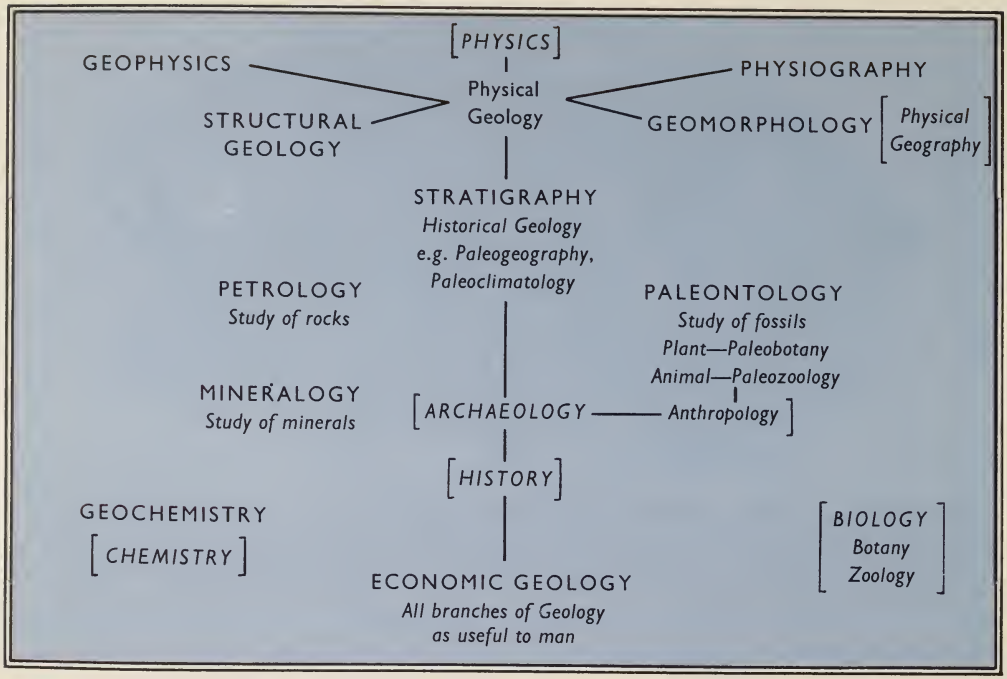
Serpentine rock and soapstone. These highly decorative rocks, which are soft and easy to carve, are formed by the alteration of basic igneous rocks. The minerals olivine and augite may react with water to give serpentine and talc, usually during strong earth movements.

These first introductory chapters have shown that many of the ideas now taken for granted have been familiar for only about 150 years and that we are still living in a time of argument and discovery.

A fundamental principle of geology is to interpret the past by studying processes which are going on at the present time. The following pages describe the changes going on in the world today, on the surface or deep inside the earth. If it is true that these processes have been operating throughout geological time, it is possible to outline the probable events of earth history. Some aspects of HISTORICAL GEOLOGY are outlined in Part Three. Then what of the future? The earth has supported a wonderful succession of life and natural beauty, from long before man appeared on it, and it may continue to do so whether or not man himself can survive. Later pages consider the world from the point of view of man and the natural resources available to him—the water and soil which are the bare necessities for life, the materials he uses for building and manufacture, and the chemicals and fuels he uses for power and energy. This is the province of economic geology in Part Four.

# EARTH SCIENCES

CHART I




The chart depicting the Earth Sciences is one of very many attempts to portray in a simple diagram the relationships between overlapping fields of study. The subjects in square brackets are closely related but not, like the rest, usually included in the Earth Sciences. There are three principal directions of study – physical, chemical and biological, and their respective disciplines unite in Stratigraphy, which attempts to put everything together into the history of the earth. Each branch of science is distinguished by a particular way of working, as much as by a distinctive subject matter, and the same material may be examined from many different points of view.

Thus a piece of rock may be examined by a paleobotanist for any plant spores or pollen it may contain, or by a paleozoologist for investigation of microscopic forams in order to interpret the past history (both these are branches of paleontology) and the organisms may be looked at by a biologist for any light they may throw on living things. On the other hand, the same piece of rock may be investigated by a petrologist, who may identify the separate minerals (mineralogy) and make a chemical analysis in order to understand the way the rock was formed. The same rock may be important to a structural geologist because it has been folded and gives a clue about the earth movements; it may have magnetic properties important in understanding the position of the earth's pole. Its resistance to weathering may be a factor in interpreting the shape of the scenery and, finally, it may contain traces of oil and be of economic importance. This example of different interests in the same material illustrates the overlapping and interconnected nature of science, and serves as a warning against specialization which can lead to isolation.

Science is not just a collection of facts but a method of finding out, and one of the wonderful things about geology is that everyone has the chance of making quite new discoveries. Man's knowledge of the history of the earth depends largely on fossils which have been knocked out of the rocks, one by one, often by amateurs, and collecting continues to be an important part of the science. The final part of this book, in some ways its most important part, discusses some of the things the amateur can do to find out more for himself. For geology is a living and developing science, in which there will always be the excitement of new discovery, and there is still a great deal more to be found out.

Trace fossil from Upper Cambrian of Pembrokeshire. Many shell fish and other marine animals which live by grazing seaweed and slime, or working systematically through mud to get the organic food out of it, do so according to a regular pattern so as not to cover the same ground twice. Some of these patterns in mud are preserved, even though the beast has left no other trace. Such relics of past life are known as trace fossils.

# *Part 2*

# HOW THE EARTH IS BUILT

## 4. Inside the earth

The deepest mines go down only a few thousand feet, and the deepest borings go to a depth of about 20,000 feet. Really deep wells are very expensive to bore, costing perhaps millions of dollars, and are not undertaken unless there is good reason to expect oil, so that only a few parts of the earth have been explored in this way. Geologists are generally dependent on deep valleys, gorges, high mountains and exposed rocks for evidence of the structure of the outer layers of the earth. Though the diameter of the earth is about 8,000 miles, the highest mountains are only about 5 miles above sea level and the deepest oceans only a little more than 5 miles below, so man can get at only a very small part of the earth directly. However, a great deal can be made of what can be seen at the surface, for rocks have been folded and tilted so that some rocks can now be seen which were once 10 or 20 miles deep.

*The temperature inside the earth*

Volcanoes have for long been thought to give a clue as to what lies beneath. The evidence of molten rock coming up from the depths of the earth, coupled with the fact that in deep mines the temperature increases gradually downwards, seems to show that beneath its surface

The upper diagram shows a cloud of steam issuing from lava in a volcanic vent. From time to time this overflows and builds up a volcanic cone of lava. The lower diagram shows an explosive volcano in which fragments of lava and rock are flung into the air and build up a (pyroclastic) cone of volcanic fragments.

the earth is very hot and in some places possibly even molten. On the other hand, volcanoes are not found all over the earth but seem to lie in belts alongside the great fold mountains. Earth temperatures, too, measured in deep mines and bore-holes, give different results in different parts of the earth, so it is difficult to make any reliable estimate of the increase of temperature with depth. In any case such increase is not necessarily evidence of great temperatures deep inside the earth. If temperatures high enough to cause volcanic activity were reached at only a moderate depth, the temperatures towards the center of the earth need not be much higher.

At first sight the earth appears to be cooling. It can easily be shown from the temperatures in mines that the surface of the earth is constantly losing heat; for if the lower part of the crust is hotter than the surface, heat must be passing out upwards. The rate of heat-loss can even be measured by comparing the temperatures at known depths. In spite of this, the surface temperature of the earth depends much more on the sun and weather than on heat from inside. In the last century physicists thought that the earth was in fact getting cooler, and this fitted in well with the idea that the earth had originated as hot gas or as a ball of molten material. It was even calculated that the earth could not be so very old since heat is still coming out at an appreciable rate.

But the discovery of RADIO-ACTIVITY has introduced a new factor. When it was found that some substances in nature disintegrate spontaneously, and give rise to enormous heat in proportion to the mass destroyed, it was realized that here was an almost endless source of heat within the earth. It was soon found that certain elements such as URANIUM and THORIUM, although existing in the earth's crust in very small quantities, could nevertheless provide a steady source of heat which would be sufficient, or more than sufficient, to replace the heat lost. It is thus possible that the earth is heating up rather than cooling. What is not known is the amount of radio-active material inside the earth. We can only measure the proportions of such elements in the outer few miles of the earth's crust. Even if they continue down less than a hundred miles, they are sufficient to replace all the

heat lost at the surface. Little can therefore be learned about the interior of the earth from the temperature at the surface today.

*The weight of the earth*

At first sight it may seem impossible to weigh the earth, but let us consider for a moment what weighing means. To weigh one object we compare it with another known object. On one end of the scale we put known weights, until the unknown material is balanced. A pound weight and a pound of butter are equally attracted to the center of the earth. As ISAAC NEWTON pointed out long ago, the earth attracts these objects just as it attracts everything, because the earth itself is large, heavy and near. Similarly, every particle of matter has its own power of attraction, depending on its weight or mass, and on its distance from the objects attracted; the greater the distance the less the attraction. This is the principle of GRAVITATION.

Numerous experiments have been devised to compare the weight of the earth with the weight of some known object. In one of these experiments a heavy mass was suspended from a very delicate balance. The reading of the scale was noted first when the mass was freely suspended above the earth. Then another mass of known weight was placed immediately beneath it at a measured distance, and a new reading taken. The small additional effect of the added mass made it possible to estimate the weight of the earth—calculated at its center, about 4,000 miles distant.

The answer means more to us if we can use it to find the earth's DENSITY, or weight per unit volume, as well. Is it as dense as IRON, as dense as stone, or as dense as water? This can be answered very simply by dividing the weight of the earth by its volume; the result is an average density about 5·6 times that of water. However, the density of the ordinary rocks of the earth's surface varies between about 2·5 and 3 times the density of water. Therefore there must be very much denser or heavier material inside the earth. If rocks similar to those of the earth's surface go down to any great depth, there must be materials much denser than 5·6 within the earth to bring the average earth density up to 5·6.

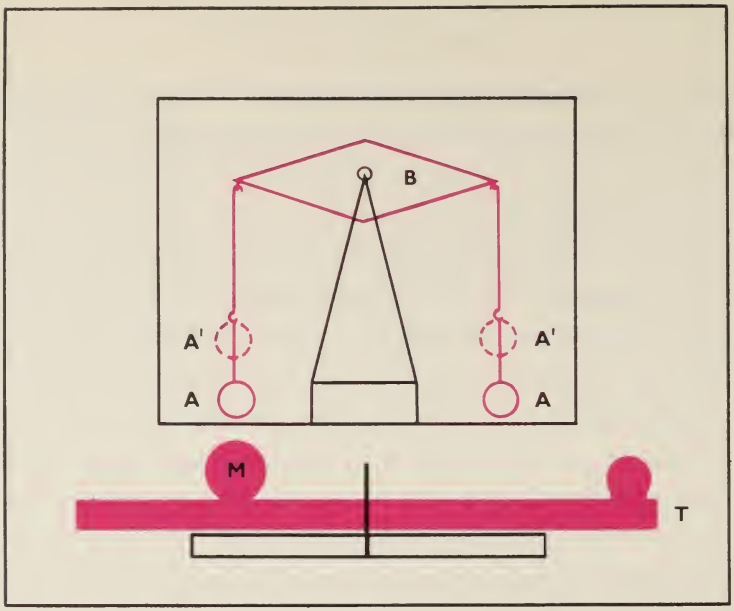



Diagram of Poynting's experiment, one of many designed to "weigh the earth". The moving parts are in red. Turntable T brings a large mass of lead M just beneath either of the two smaller masses A and B on a balance. The attraction of known mass M at distance AM is compared with the attraction of the earth, whose centre is at known distance, but of unknown mass. The distance AM can be varied (A'M). To do this experiment with sufficient accuracy it is controlled from outside an insulated room and the balance is in an insulated box.

When material is compressed under a very great weight it becomes smaller and more dense. An increase in the density of material near the center of the earth is therefore to be expected. But in addition to this automatic increase due to compression, there may be still further increase in density due to a difference in materials. The center could be iron, LEAD, or GOLD, for instance, or something else really dense.

What other clues are there to the nature of the earth's interior?

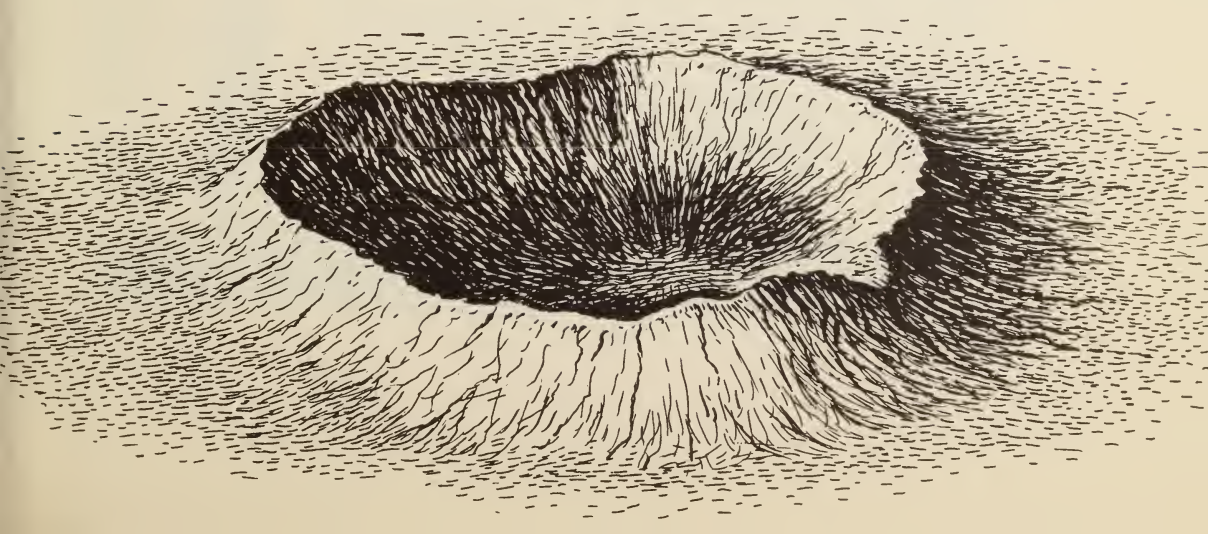
*Meteorites*

The shooting stars we often see in the sky are known as METEORS. They are small particles in the solar system – or sometimes quite large masses – which come within the earth's gravitational pull and heat up when they encounter the friction of the ATMOSPHERE. Usually they burn out long before they reach the earth, but if, as occasionally happens, one of these bodies does reach the earth, it is known as a METEORITE.

Some meteorites are stony, and very similar in character to some of the basalts and other dense rocks known at the earth's surface, though no meteorite yet found has resembled granite. The better-known type of meteorite is that which consists of iron with some NICKEL. These have occasionally been found in regions with no native iron, and have consequently been mined and put to practical use. A very large iron meteorite found in Greenland was used for many years by the Eskimos for their weapons. A third kind of meteorite is a mixture of the first two, and is called a STONY-IRON.

From many observations we now know that these meteorites, before they hit the earth, belonged to the solar system together with the earth and the other planets. We also assume, because we have no reason to do otherwise, that all the planets, including the earth, had a similar origin and have some common features – as well as some marked differences. In meteorites the mineral and crystal structures observed strongly suggest that they were once part of large planet-like bodies. How such a body, or bodies, came to be shattered into many fragments is not known, but a possible explanation would be that two small planets collided long ago. Anyway, meteorites have long been thought to provide clues about the interior structure of the earth and other planets. The fact that stony meteorites are so similar to the rocks on the outside of the earth fits well with this idea. Also the

Meteor crater, Arizona. This is one of the best known craters which is certainly not volcanic, but due to the impact of a large meteorite. The crater is due to explosion on impact, but there is no volcanic rock. The meteorite itself probably disintegrated and penetrated to depth.



existence of iron and stony-iron meteorites tallies with our evidence that the center of the earth contains a dense CORE. Since iron is one of the more common metals in the earth, it is not unreasonable to think that the earth's core may be composed mainly of iron.

*Magnetism*

Such a mass of iron in the center of the earth has been suggested as the cause of the earth's MAGNETISM, but despite much careful study there is still no really satifactory explanation of this phenomenon. If there were simply a large iron magnet within the earth then its magnetism should remain constant, but in fact it varies considerably. We know that the direction of magnetic north changes from year to year, and over many years the position of the magnetic poles may swing 20° or so in different directions.

Recent studies suggest that magnetism is due not to a solid magnet, as was first thought, but to movements of some fluid in the earth's center, behaving rather like a dynamo. If this were so it could happen without the presence of iron, and therefore the magnetic properties of the earth do not necessarily suggest an iron center, but neither do they argue against it.

*Tides*

The ELASTICITY of the earth provides another possible line of evidence. The earth's shape, which is nearly spherical but slightly flattened at the poles, is just about what would be expected for its size and rate of spinning. This shape is what we would expect whether the earth was solid or liquid inside. There are, however, a number of disturbances which affect the earth, and the way the earth reacts to these gives some idea of the strength and elasticity inside. For instance, as the earth rotates in relation to the sun and the moon the water on its surface is attracted towards them. If the earth were largely liquid, there would be no TIDES visible at the surface, because the crust itself would be pulled towards the sun and the moon to the same extent as the seas. That the earth is not pulled out of shape so much as the seas shows that it is much stronger than a fluid earth could be.

This sort of argument can also be applied to other rather complex astronomical motions which the earth performs, and the results tell us that the earth cannot possibly be mostly liquid with a thin solid crust. On the contrary, the earth behaves as a rigid solid, and whatever liquid may be within it can form only a small part of the whole.

*Earthquake waves*

Finally, EARTHQUAKES provide more information than nearly all the other sources put together. Earthquakes are due to waves which have traveled through the earth from some disturbance, usually well below the surface, where rocks have broken or cracked and moved in relation to each other. This is happening almost continuously, although it is only the larger occurrences that we know about because of the devastation which follows. We tend to think of earthquakes only as catastrophes resulting in broken cities, dislocated communications, tidal waves and many other dramatic happenings. To a scientist, however, earthquakes, both small and large, have immense use; they can be detected by continuously-recording SEISMOGRAPHS located at observatories in many parts of the world. Seismographs record even

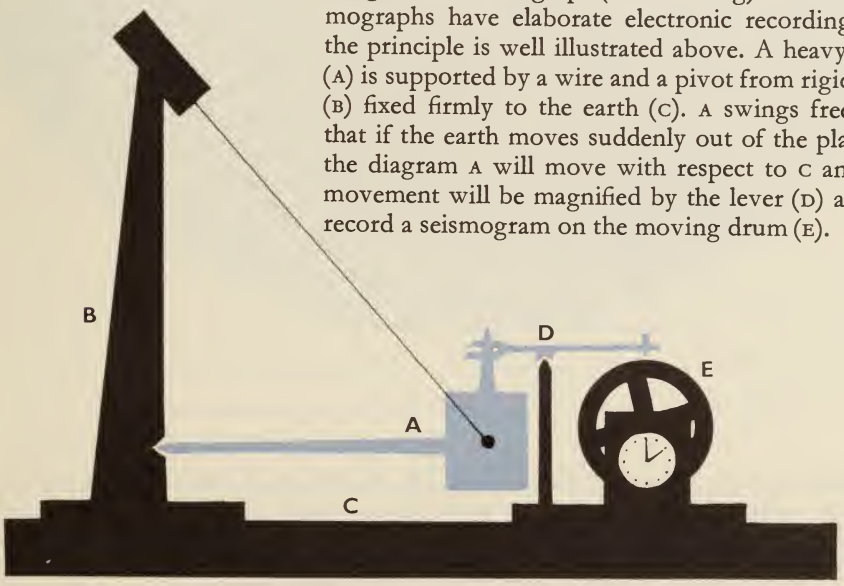
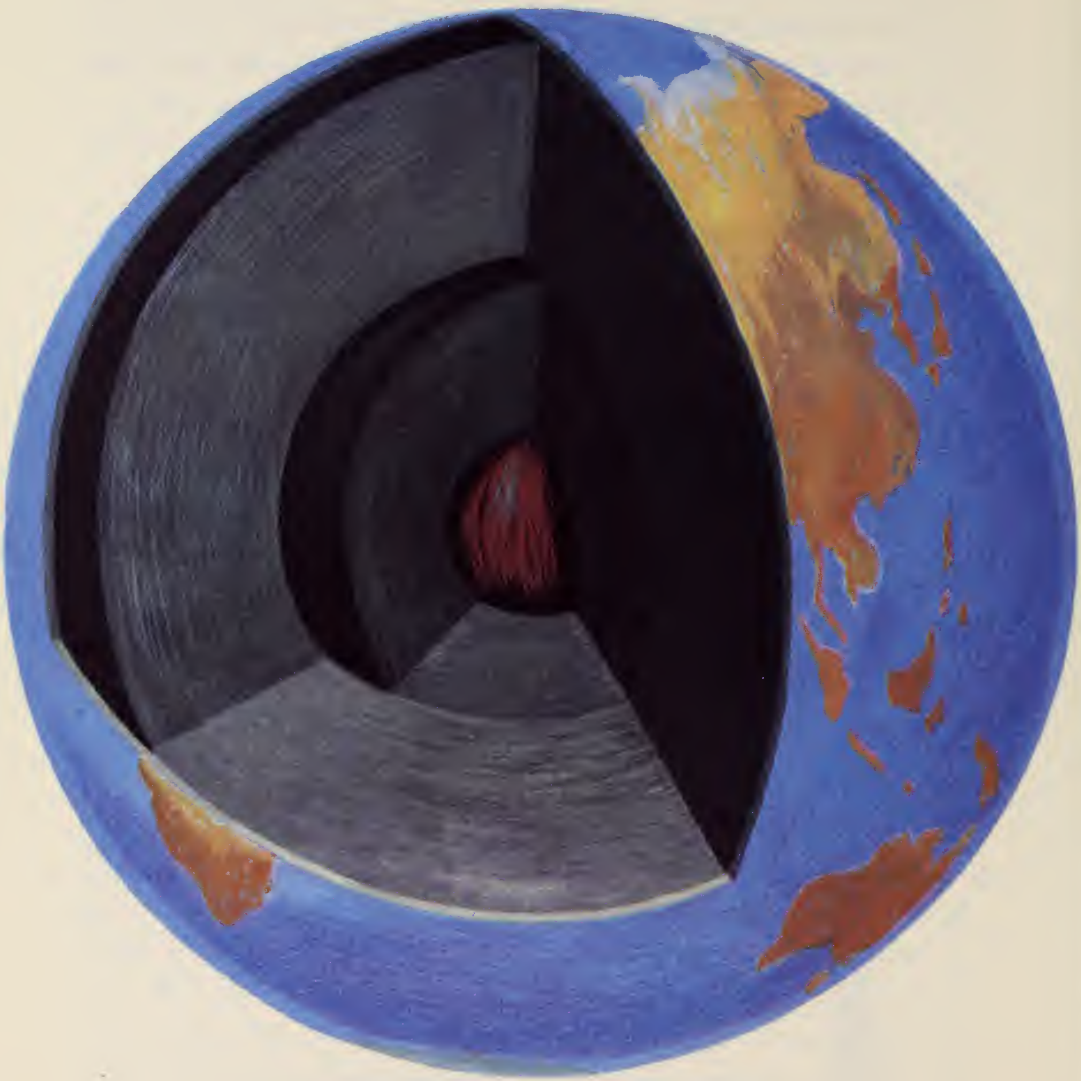



Diagram of seismograph (after Sieberg). Modern seismographs have elaborate electronic recording, but the principle is well illustrated above. A heavy mass (A) is supported by a wire and a pivot from rigid post (B) fixed firmly to the earth (C). A swings freely so that if the earth moves suddenly out of the plane of the diagram A will move with respect to C and the movement will be magnified by the lever (D) and so record a seismogram on the moving drum (E).



Cutaway model of the earth. The radius is about 4,000 miles. The crust varies from about 5 to 50 miles. The mantle lies below this to a depth of about 1,800 miles, and appears to be solid, while the core appears to be fluid. However, an inner core may be solid.

the smallest movements of the ground and also the exact time when the movements take place. The principle is simply that a large weight is suspended freely so as not to move readily when the ground shakes. In an earthquake everything moves except this weight. Through a device which magnifies EARTH MOVEMENTS, they can be automatically recorded on moving paper as a wavy line – the SEISMOGRAM.

Three quite different kinds of earthquake waves are known, all of which travel from the earthquake at the same time, but in different ways. The easiest to imagine but the most difficult to understand properly are known as SURFACE WAVES, or L-waves. They travel in various ways along the surface of the earth and are usually responsible for the most violent effects of an earthquake. When the ground is felt to be rolling the motion is caused by a surface wave.

The two other sorts of wave pass right through the solid earth. One sort is known as a PRIMARY WAVE, or P-WAVE, and is a push-pull wave just like a sound wave. A series of zones of alternate compression and expansion spreads outwards from the center, shaking the earth so that each particle moves backwards and forwards in the direction of travel of the wave. The other sort of wave passing through the body of the earth is known as a SECONDARY WAVE, or S-WAVE. This wave causes the earth material to shake from side to side instead of forwards and backwards, and is known sometimes as a shake-wave; it can only travel through a solid.

The P-wave travels faster than the S-wave and therefore arrives at the seismographs first; when the S-waves arrive they are mixed up with the disturbance due to the P-waves. The surface waves travel slowest of all but their disturbance is very much greater when they arrive. It is thus possible on a seismograph record to distinguish the arrivals of the different sets of waves. It is also possible, by carefully comparing distant seismograms recording the same earthquake, to work out the exact route traveled by the first of each kind of wave to arrive.

From this information a number of very important results have followed. One of these is the discovery that the velocity of the P- and S-waves increases with depth. As it is known that their velocity de-

pends on the elasticity and also on the density of the part of the earth they are traveling through, we can get some idea of the elasticity and density at different depths below the earth's surface. It has been found that there is a number of rather sudden changes. There is, for instance, a sharp increase in velocity varying from say 30, 40 or 50 miles below the continents and perhaps 5 or 10 miles deep below the ocean beds. This depth at which the wave velocity changes is known as the MOHOROVIČIĆ DISCONTINUITY (or "Moho"), and it separates what is known as the crust of the earth from the mantle beneath. In the mantle itself there are further changes in velocity showing that there must be differences in the state of matter at various depths.

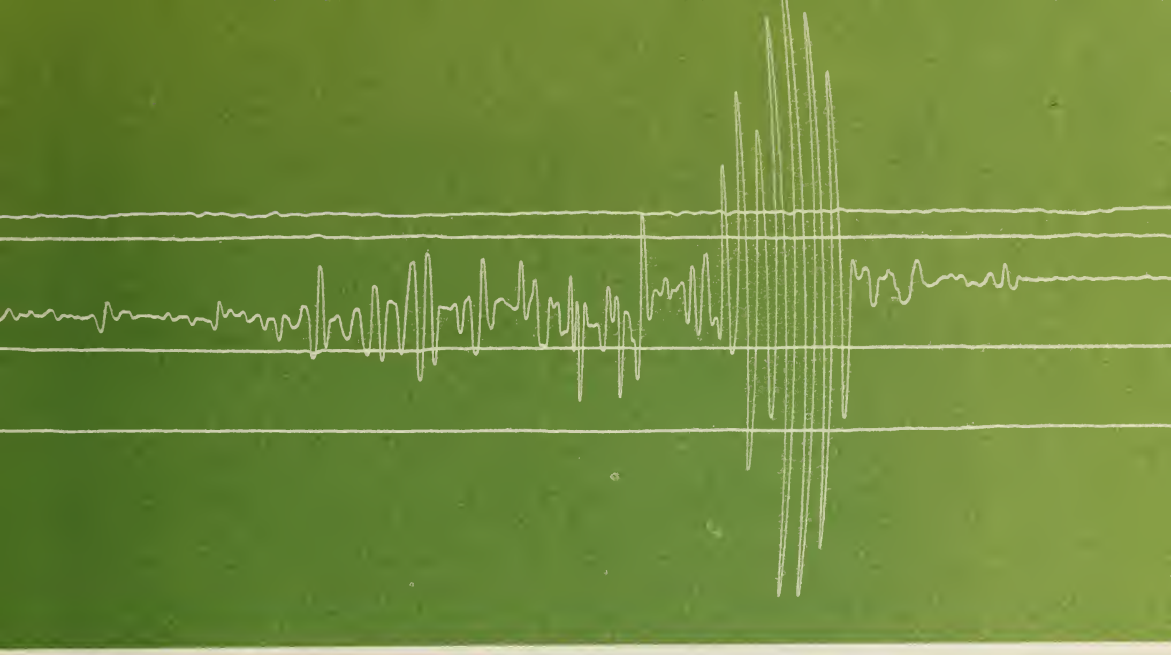
Perhaps the most dramatic of all the findings is that, at a depth roughly half-way to the center of the earth, S-waves are stopped, but P-waves continue unimpeded. This is explained by assuming that there is a change to fluid, because whereas sound waves can travel through a solid, a liquid, or a gas, the S-waves can only pass through a solid. It is, therefore, generally accepted that part of the center of the earth is fluid. This fluid part is now known as the core, as distinct from the MANTLE above.

There are many other interesting things to be learned about these inner regions. Possibly within the fluid core there is an inner core which may be solid. If so, this would be difficult to detect because it would be shielded by the outer fluid core from any S-waves, and would have to be identified by some other type of evidence.

There are therefore three main parts of the earth – the crust on the outside, which is about all we can expect to know from studies of rocks; the mantle, which occupies about half the diameter of the earth but, of course, far more than half its volume; and the core, which again is about half the diameter of the earth but a great deal less than half the volume.

The important thing about earthquake evidence is that it enables us to estimate definite depths for these various features and that it provides some quite useful information about the nature of the material at those levels.

Thus the study of the inside of the earth depends on a great num-



This is an actual copy of a seismogram (the record made by a seismograph). For economy the trace continues round and round the drum, and if there is no movement will appear as a series of straight lines. Movement is recorded as deflections whose exact time can be found. The larger deflections are curved and show that the pen was swinging on a lever while the paper moved slowly outwards. This seismogram was made in London, and records an earthquake which took place in Algeria on September 9th 1954. (British Crown Copyright, Science Museum, London.)

ber of different clues. As in a detective story, each clue by itself may lead to very little, yet each is important because it may be an essential link in the argument. There is still a great deal more to be discovered, which will, no doubt, depend on still further ingenious applications of the latest physical knowledge to the understanding of the deeper parts of the earth.

The evidence considered in this chapter depends on observations made on the earth today. But the study of the rocks on the earth's surface reveals a long and rather complex history which is clearly related to the internal changes of the earth. Any theory about the inside of the earth must, therefore, also fit what the rocks can tell us of the complicated history of the earth during the last three thousand million years or so. This quite different line of direct evidence will be considered later.

# 5. The outer layers

*The atmosphere*

The outermost layer of the earth of which we are conscious is the atmosphere. Only recently, since rockets and artificial SATELLITES have been launched from the earth, have the upper regions of the atmosphere been penetrated. However, it has long been known that towards the tops of the high mountains the air becomes rarefied, and above this it is so thin that oxygen must be carried and aircraft be pressurized to sustain life. The air gets thinner and thinner with height, and while it is difficult to say exactly where the outer limit is, there is no doubt that most of the air around the earth's surface is concentrated in the lower 10 miles.

The weight of the air can readily be found because BAROMETER readings are, in fact, a measure of this weight. At sea level, where the pressure of the air is greatest, it is capable of supporting a column of MERCURY about 31 inches high, or over 30 feet of WATER – that is to say, the total weight of the whole atmosphere would be equal to a layer of about 30 feet of water around the whole earth. At a height of 10,000 feet the pressure would fall to 20 inches of mercury, and at 20,000 feet to 14 inches – which shows that more than half the atmosphere is below 20,000 feet.

The air consists of about four parts of NITROGEN to one of oxygen, plus a small proportion of CARBON DIOXIDE and water. The oxygen is necessary for life and is involved in many chemical reactions in rocks; the carbon dioxide is essential for plant life. The water vapor plays an

Cave with stalactites (hanging) and stalagmites rising from floor. Dripping water saturated with lime after soaking through limestone will deposit calcium carbonate when it emerges from the limestone. The release of pressure allows carbon dioxide to escape, and the soluble calcium bicarbonate changes to calcium carbonate and is thus deposited. The process is very slow and the rock formed may be stained by traces of impurity.

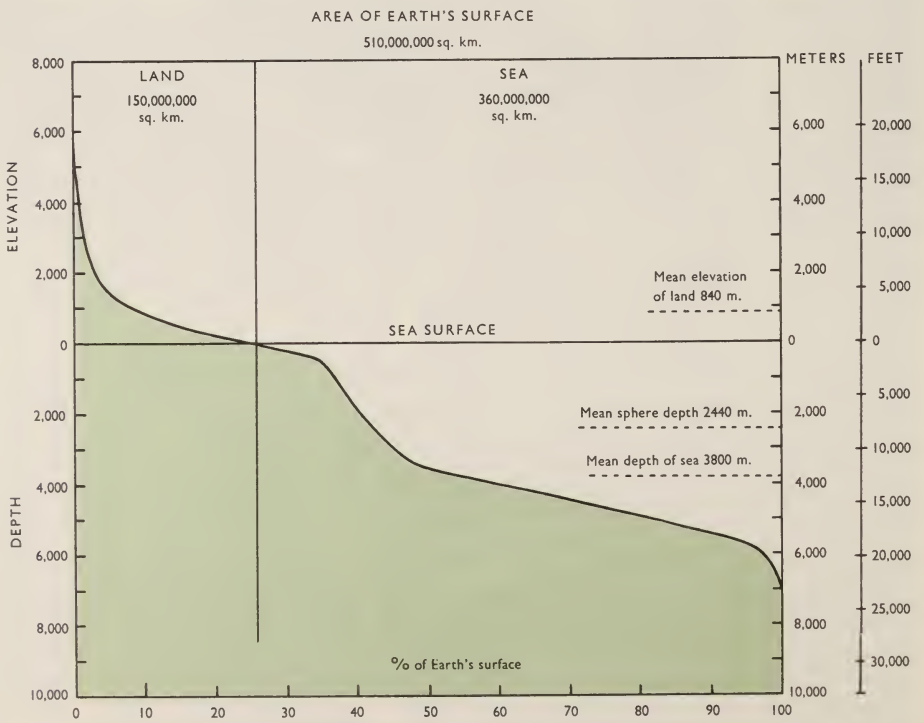
important part in the circulation of water throughout the earth. ARGON, HELIUM and other inert gases are present, but not easily distinguishable.

*The hydrosphere*

While the atmosphere is roughly a sphere around the earth, the HYDROSPHERE, or layer of water, is not so regular, because it occupies the oceans, seas, rivers and lakes, which penetrate upwards into the atmosphere and downwards into the earth. The average depth of water if it were spread evenly over the globe would be $1\frac{1}{2}$ miles.

Water is constantly being evaporated from the surfaces of seas and lakes, and carried as water vapor in the air until precipitated as rain or snow, which falls on sea or land. If it falls on the land it temporarily penetrates into the ground, evaporates, or runs off the surface in

The Hypsometric (or Hypsographic) Curve is a diagram to show the relative areas of the earth's surface at different heights above, or depths below, sea level. Thus 74% of the earth's surface is covered by sea and 46% by sea at depths greater than 3,800 m. The flattened parts of the curve show the commonest heights and depths.



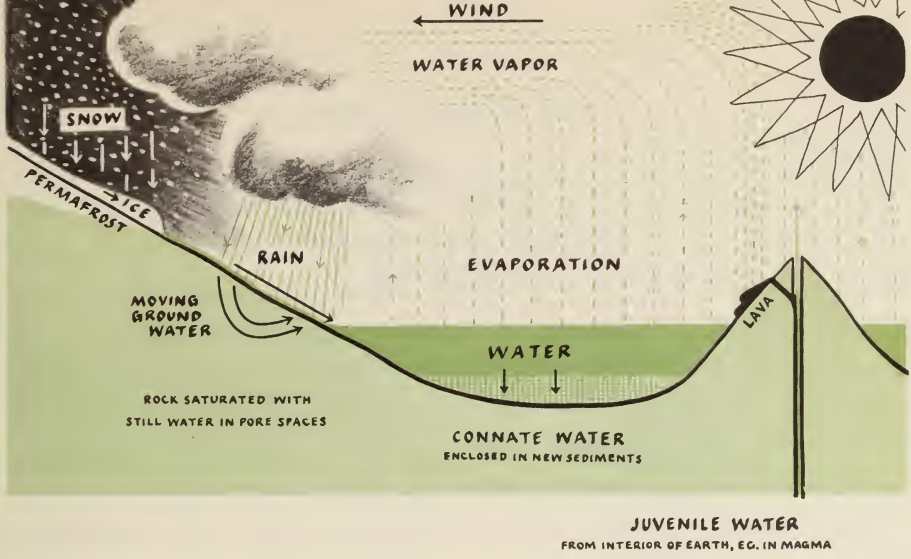



Diagram to show the circulation of water near the earth's surface, known as the water cycle. Most water circulating is known as meteoric water; the main reservoir is the ocean, from whence it is lost by evaporation and returns by various routes. Juvenile water is constantly being added to the meteoric water from the depths of the earth; connate water is removed from the water cycle for long periods in sedimentary rocks.

rivers and flows back to the sea. Thus it makes a complete circuit, known as the WATER CYCLE, and the same water appears to go round and round incessantly.

*The biosphere*

Those who like to regard the various parts of the world as a series of "spheres" refer to the layer of living things scattered over the surface of the earth in water and on land as the BIOSPHERE. The total weight of this "layer" is relatively small, for averaged out round the world it would amount to a layer only one inch thick. Living things are composed very largely of carbon, HYDROGEN, and oxygen, with a little nitrogen and PHOSPHORUS and traces of most other elements. The biosphere is important in geology, partly because of the fossil record of life, and partly because of the way in which living things affect the formation and breaking down of rocks.

*The lithosphere*

All the spheres mentioned above rest on what is sometimes called the LITHOSPHERE (the rocky sphere), but as this term is not clearly defined with respect to the lower boundary it is better to refer to the crust of the earth if a distinct layer is intended. In the last chapter we

## TABLE 1

Proportions of the elements in common rocks

| *Element* | *Symbol* | *Weight per cent* |
|---|---|---|
| Oxygen | O | 46·60 |
| Silicon | Si | 27·72 |
| Aluminum | Al | 8·13 |
| Iron | Fe | 5·00 |
| Magnesium | Mg | 2·09 |
| Calcium | Ca | 3·63 |
| Sodium | Na | 2·83 |
| Potassium | K | 2·59 |
| All other elements | | 1·41 |

saw that the inner boundary of the crust is defined by the "Moho" Discontinuity, and that it varies in thickness from perhaps 5 miles at its thinnest parts to about 50 at its thickest. The composition of the whole of the crust is probably similar to that of its surface rocks, and on this basis various people have estimated the proportion of different elements. Table 1 gives the proportion of the common elements in a number of common rocks, averaged out so that the commonest rocks carry most weight.

Our impression of the crust of the earth comes largely from the continents, for very little is known about the bottom of the oceans. Since three-quarters of the earth are covered by water, it is only a small part of the earth's surface about which we have any detailed knowledge. The familiar patterns of the continents seen in atlases show only the coastlines, but the continents extend quite a long way beneath the seas as the CONTINENTAL SHELVES: indeed at some distance from the shore the water is often relatively shallow. Then the depth increases steeply down the CONTINENTAL SLOPE to the depths of the oceans. In geology the continents are taken to include the continental shelves as well as the dry land, and therefore cover a larger proportion of the earth's surface than the dry land alone.

Even if the sea level were raised by only 100 feet, quite a considerable change would take place in the proportion of land to water. Most of the capital cities near the sea would be flooded, and all the ports and many coastal plains would be inundated. The illustration on p. 54 shows the proportions of land imagined at different sea levels, and from this we see that there would be a predominance of land at a level not far below the present sea level. Areas containing very high mountains are relatively small. There is a steep slope down from the continental shelf to the ocean floor, much of which lies at an average depth of about 12,000 feet below sea level. Both the highest mountains and the deepest parts of the ocean occupy only a small part of the earth's surface. Thus two levels predominate, and the upper one is very close to sea level.

This may be explained partly by the struggle between land and water. Through the ages the sea has been slowly creeping over the land and washing away the cliffs, and rivers have been carrying sediment down to the seas. If this process were continued long enough, it would seem that the whole land would be reduced nearly to sea level, and that the sea must in the end win. But there are other forces the sea has to contend with, forces deep down in the earth, which can raise new land and new mountains, often from sediments formed beneath the sea. These two opposing forces – the surface forces and the deep forces – will be the subject of the next two chapters, and we shall see how the balance between them throughout the ages has led to the present distribution of land and sea.

The deep forces have certainly prevented the continents from being entirely worn away, and we may wonder whether there have always been continents and oceans as there are today. More and more knowledge about the ocean floors is being obtained by research ships, from which instruments are let down on long cables to sample the bottom, photograph it, and record measurements there. We can also get some idea of the nature of the floor of the oceans from volcanic islands. The continents have a rather similar average composition, but this differs greatly from what is known about the average composition of ocean floors. Briefly, the composition of the continents is more like

This coastal scene illustrates the interplay of surface and deep forces. The flatlying rocks were probably deposited beneath the sea, and the flat cliff tops are part of an earlier extensive peneplain about sea level. The land has been uplifted since that time and steep cliffs and a ravine show the renewed attack of the sea. The uplift has given the surface forces new energy – a process known as rejuvenation.

granite, sandstone, limestone, and shale, while the composition of the rocks beneath the ocean floor seems to be much more like basalt. There is, of course, basalt on the continents, but it forms only a small proportion of them, whereas in the oceans it may well account for most of the rocks beneath the superficial sediments. From this it follows that the rocks of the continents are not so heavy, or dense, as the rocks of the oceans. It seems that the average density of continental rocks is something like the average for all metamorphic rocks (say 2·7 times the density of water), and the average density of oceanic rocks is more like that of basalt (say 3·0).

*Gravity survey*

Scientists can be fairly sure of the densities of these two groups of rocks by weighing them in much the same way as they weigh the earth.

The previous chapter showed how gravity can be used to compare the weight of the earth with that of a smaller body just beneath a balance. With very sensitive instruments developed in the last few years, the earth can be weighed very accurately, and its apparent weight has been found to differ in different places. This seems to be due to the effect of the different densities of rock just beneath the instruments. If, for instance, there happened to be a very large cave under the instrument, the earth would seem to be lighter, but if the cave were filled with gold the earth would seem to be heavier. By measuring very accurately the weight of the earth by its gravitational pull and knowing that the whole earth can only have one weight, scientists can estimate the differences in density of the parts lying beneath the instruments. When doing this they must take into account the height of the instrument above sea level, as the earth appears to weigh less from higher up. Account must also be taken of the distance from the equator because the spin of the earth at the equator (CENTRIFUGAL FORCE) will tend to make the earth seem lighter there than it would at the POLES.

When these allowances have been made the earth really does appear to weigh very much the same in different places. For instance, if measurements are taken near the surface of a deep ocean – as can be done in a submarine – the result is very much the same as it is when the same instruments are used on land at about sea level. This was at first surprising, because sea water is much less dense than rock. The only way we can explain this result is by assuming that the rock underneath the oceans is more dense than the rock of the land, and that its greater gravitational pull makes up for the less dense water above the ocean floor. This, of course, fits in very well with the idea that the oceanic rocks are basalt, and denser than the rocks of the continents.

So by the measurement of GRAVITY we have a method of finding out where the light and dense rocks are in the earth's crust. This method, known as GRAVITY SURVEY, gives information only about the surface layers of the earth, but it is important information. The highest parts of the earth's crust appear at first sight to be made of the lightest rocks, and the deepest parts of dense ones. This was dis-

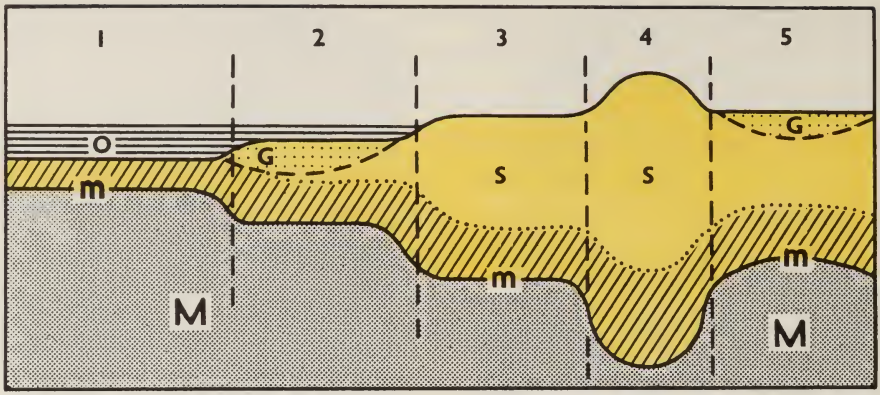



Diagram to show a section of the earth's crust (colored yellow), which is separated from the mantle (M) by the "Moho" (m). The sial (S) is of density about 2.7 and includes new geogynclines (G). The sima above the "Moho" is of density 3.0, and the upper mantle of density about 3.3. O indicates the sea.

These materials of different densities are arranged in such thicknesses that high ground is supported by a thicker "raft" of less dense crust, while the light ocean (density 1.0) is underlain only by denser sima. Gravity measurements show that equal areas of the earth's surface are underlain by approximately equal masses, and this equal standing is known as isostasy.

covered when, during the first accurate survey of India, the sideways attraction of the Himalaya mountains on the spirit level in the THEODOLITE was found to be less than was expected. It was eventually concluded that the high parts of the mountains had been raised by the buoyancy of lighter material resting on and pushing down into the denser material beneath.

*Isostasy*

This idea that the weight of the higher parts of the earth's crust is compensated by low-density rock extending deep down, is a very important one in geology, and is given the name of ISOSTASY, which means equal standing. The idea is roughly that any two equal areas of the earth's crust, high or low, will weigh about the same. If there is more of it, as in a mountain chain, it will not be so dense, and if there is less, as beneath a deep sea, it will be more dense. This gave rise to the idea of continents as "rafts", and mountains as "icebergs", floating in a more dense layer. This fits well the conclusions drawn from earthquake waves, for the "Moho" discontinuity is deeper be-

neath the higher mountains and continents than it is beneath the oceans. But the familiar picture of continents floating as "rafts" in an ocean of basalt is not ideal, for the basalt in which these rafts are thought to float is a very tough rock, more difficult to melt and stronger than the continents themselves.

One effect of isostasy is that if material is removed from the mountains they will become lighter and tend to rise, just as a raft would if the load were removed. Likewise the same material carried by the rivers and dumped in a DELTA, will make the delta heavier and will tend to sink.

So because of erosion, TRANSPORT and deposition, the crust has to keep moving to maintain a state of balance. In some parts of the earth there is much UPLIFT and erosion, but other parts appear to be quite stable for very long periods. Moreover, at different times different areas have been affected by great earth movements.

One of the most difficult problems in geology, in fact, is to account for the way in which a mountain chain can be continuously eroded and uplifted, so keeping the mountains at about the same height for a very long period. Similarly it is difficult to account for the continual sinking of deltas some thousands of feet as small amounts of sediment are added to the top layer, which tends to remain near sea level. The adjustment to changes of load seems to be a very delicate one, and the simple raft idea does not work very well.

It is possible that the delicate adjustments to load at the surface may be the result of changes in the material at the "Moho" level. The idea is that the material below the "Moho", although certainly more dense, is of the same composition as the material above it—something like basalt. Under great pressure basalt may change into a rock rich in GARNET. Garnet is a dense mineral only formed at great depths. The removal of material by glaciers and streams from a mountain range would reduce the load deep down at the "Moho" level, with the result that the garnet-bearing rock might expand, changing back to basalt (or GABBRO) and so uplifting the mountain.

This idea is not certain, but if it is true we have a picture of the crust of the earth as shown on page 48 in which the continents (largely of

Diagram of waterfall flowing over a layer of resistant rock which protects the underlying soft rocks upstream, but once removed allows rapid erosion of a gorge down-stream.

metamorphic rocks with sedimentary and igneous rocks) extend deep down into the crust. The material deep beneath the continents and immediately beneath the oceans is of gabbro. Less than 10 miles beneath the ocean level and less than 50 miles beneath it in the continents, is the "Moho" level, below which may be ECLOGITE. Both gabbro and eclogite are coarsely crystalline rocks of basaltic composition, the eclogite, due to the mineral garnet in it, being denser (3·3) than the gabbro (3·0).

These, then, are some of the problems associated with the outer layers of the earth's crust. It is very important that we should find out more about them because the geological events we study take place in the outer layers. We know a great deal about the processes which go on at the surface of the earth, and the "SURFACE FORCES" will be reviewed in the next chapter. The chapter on the "DEEP FORCES" which follows is full of difficulties. We know that deep in the outer layers, and even deeper still, there are forces which cause earth movements and volcanoes, but very little is known about them.

# 6. Surface forces at work

Most of the natural forces working at the surface of the earth depend ultimately on the sun's heat. These days we are rightly impressed by the energy released, for instance, in a nuclear explosion, but the total energy of recent explosions is small compared with the tremendous forces of winds and the atmospheric circulation. The movement of the air all over the earth's surface and at great heights above it is ultimately due to the heating of air in some places, causing it to expand and rise, and the cooling of air in other places, causing it to contract, fall, and flow under the warmer air.

Winds near the earth's surface are movements of air from regions of high pressure to regions of low pressure, and they are compensated by winds high above the earth's surface, blowing in the reverse direction. One of the most important effects of this circulation is the removal of water from the oceans by evaporation into the air, and its transference over considerable distances by winds, until it is dropped as rain or snow. From the land it is returned, in time, by various routes to the sea.

Much of the breaking-up of rocks by weather, the transport of débris and the final laying-down of this débris is due to the circulation of the atmosphere and of water.

*Attacks on the rocks*

There are several ways in which rocks are attacked. One of the most important, in moist climates, is what is known as chemical WEATHERING. Many of the minerals in rocks were formed at high temperatures and pressures, as for instance minerals of igneous and metamorphic rocks, or minerals derived from these rocks and now preserved in sedimentary rocks. These minerals may be unstable at the ordinary temperatures and pressures at the earth's surface, and they decom-

pose easily. Water percolating underground from the surface, charged with gases such as oxygen and carbon dioxide, will tend to decompose some minerals. During some of these processes water is added to the mineral and it expands. If only a few minerals in a rock decompose in this way the whole rock is weakened and will gradually crumble and decay. In the course of time it may form soil or dust. In limestone, the minerals dissolve almost completely in water and the rock gradually disappears, leaving behind only an insoluble residue in the soil.

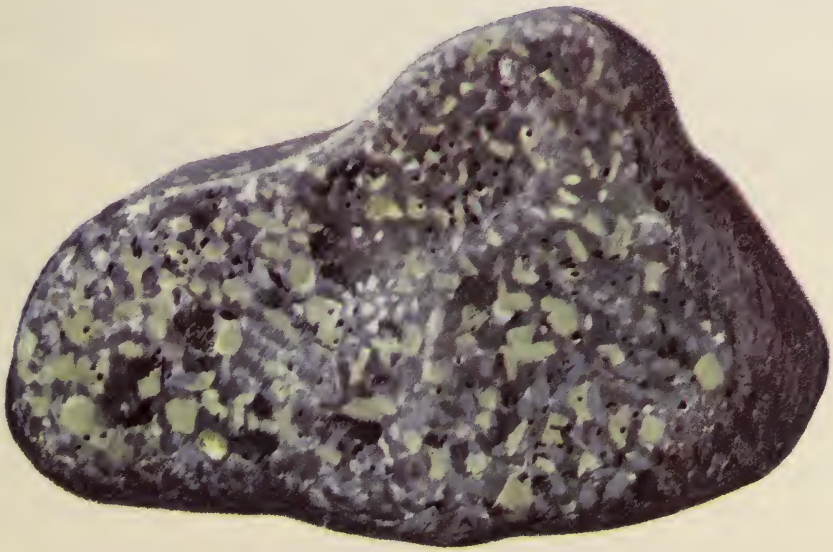
Chemical weathering is inseparable from physical DISINTEGRATION. The first is the breakdown of the individual minerals and the second the breakdown of the rock itself which follows. Sometimes disintegration is due to new salts crystallizing from solution and forcing open the cavities in which they are growing. This happens in hot deserts where evaporation from the surface brings these salts up from below. In desert countries disintegration is also caused by rapid changes of rock temperature. On heating, rocks expand, and on cooling they contract, so that when rapid changes of temperature take place the surface of rock may expand more quickly or cool more quickly than the inner part, and cause pieces to flake off. Also minerals, whose expansion with temperature differs, set up stresses in the rock which may break it.

In cold climates ice may be formed in the crevices of the rock. When water turns into ice, there is a tremendous force of crystallization, because the ice is of greater volume than the water from which it was formed. Thus, on freezing, the water in a rock will tend to expand the rock and possibly shatter it.

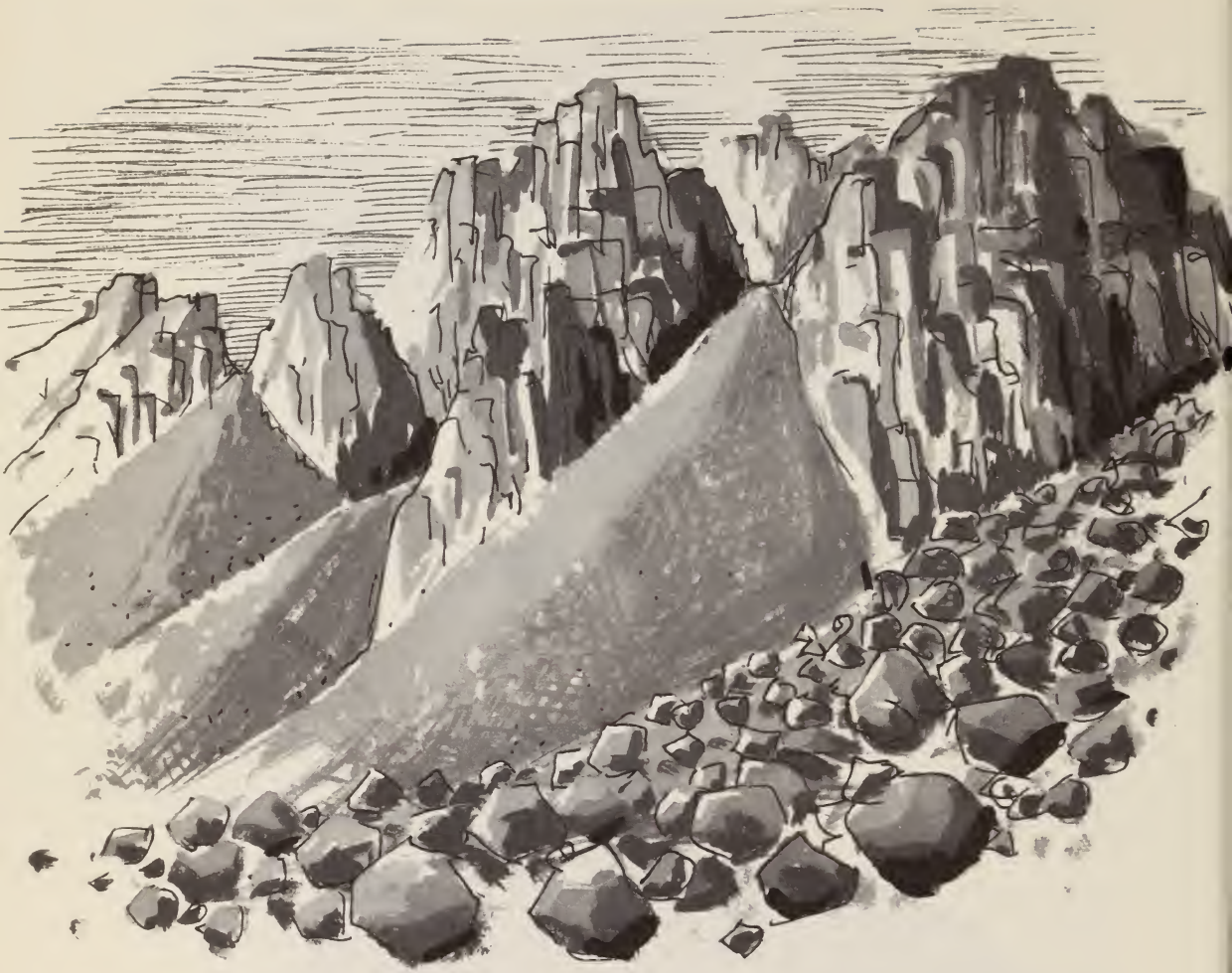
So there are various ways in which rocks are attacked by the weather, and in many climates different seasons of the year favor different processes.

Weathering is most noticeable when the products of weathering are left for us to see, where rocks are not actively cleaned or eroded, but where the débris is allowed to accumulate in the soil. This applies to the surfaces of most rocks. Throughout most of the earth's surface the rock is covered by a layer of soil due to weathering. Where such

Fragment of stalagmite (see illustration on page 52) showing layers built up of precipitated calcium carbonate. Although too small to distinguish, the calcium carbonate is usually in the form of minute crystals of calcite.



Water-worn pebble of grey granite. Granite is made up largely of crystals of feldspar and quartz and this illustration shows their size in a typically coarse-grained igneous rock.



In rugged mountains detached rock fragments slide down the hills and accumulate as steep slopes of talus. Such deposits may keep moving, at least near the surface.

soil is allowed to accumulate, and where the climate is suitable, plant growth may cause the penetration of the rock by roots, and the accumulation of decaying vegetable matter may give rise to organic acids which themselves dissolve the rock. Burrowing animals such as worms may also have quite an important effect. Man adds to the natural destruction of rocks as he cultivates the land, destroying the natural accumulation of soil, and allowing more rapid weathering of the rocks beneath.

Where the rock is not covered by soil a still more active form of attack may take place. Such rock may be directly exposed to the blast of wind, the rush of water, or the grinding of ice. It is important to notice, however, that by themselves neither wind, water, nor ice, would have much effect on the rock, which is so much harder. Their attack really depends on the particles of rock they carry. When so charged, they can wear down any exposed rock, as is well known from the curious shapes produced in desert rocks and pebbles, and from the effects of powerful erosion in streams, incessant attack by waves on the seashore, and by seemingly motionless ice, which is nevertheless capable of carrying the largest boulders.

*Removal of rock waste*

The waste matter formed by the breakdown of rocks into small particles or into solution, if allowed to accumulate, would in due course protect the underlying rock from further decay. Removal of the products of decay is therefore a second and essential element in the erosion of the landscape.

One of the most widespread processes, but perhaps the least obvious, is the one known as MASS WASTAGE. This is a process in which the surface layers creep bodily downhill. This proceeds very slowly, but it may affect several inches or feet and have quite an important result in the end. There are various ways in which it can take place. For instance, it is clear that any loose surface material will tend to slide down rather than up a slope, and any disturbance repeated often enough will cause the downward motion. One simple disturbance is the expansion of the soil when water in it is frozen, and when this happens on a slope the soil moves outwards and not vertically upwards. When the ice in the soil melts, the soil contracts and moves downwards. Thus each expansion and contraction will result in a slight zig-zag movement downhill.

A more important process may result when freezing takes place and plenty of water is available. For the crystals of ice in frozen soil continue to grow if they are fed by water percolating beneath it. In this way soil may draw into itself much more water, in the form of

Ripples in shifting sand are due to strong desert winds which in the above illustration have probably blown from right to left. On a larger scale the same process forms sand dunes. The slopes seen in the illustration are part of large dunes. Often, a desert consists of bare rock with stones from which all the sand has been blown.

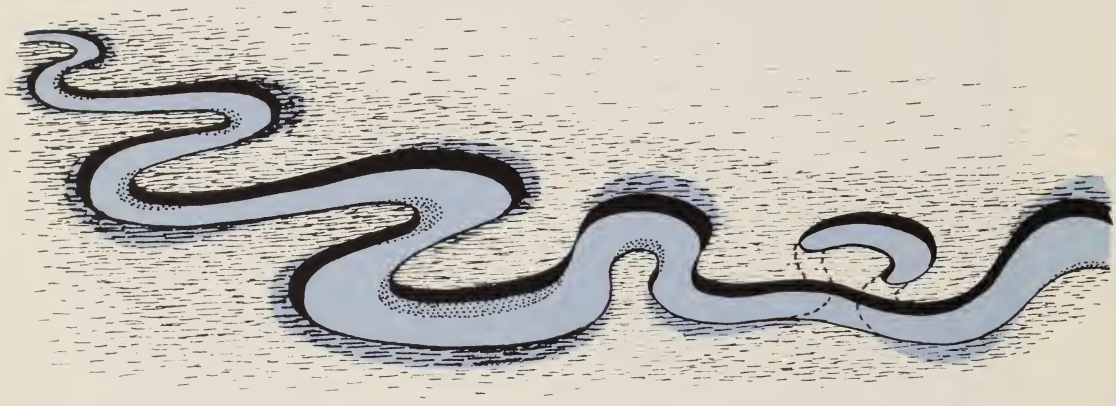
ice, than it had at first. The result, as seen on the surface, is known as FROST-HEAVING and may be quite destructive. When this sort of frozen ground thaws it leaves a very wet mud, because the soil now has far more water than it could normally hold. Such highly fluid mud on any slope is likely to flow, and mud-flows are well known in Arctic countries where freezing of the ground is a regular occurrence. On the other hand, mud flows may be simply the result of heavy rain. In either case the result, known as SOLIFLUXION, may have important effects.

Rock waste may also be removed in the air. Unless soil is well

protected by a covering of vegetation it will sometimes dry out to a fine powder which is quite easily removed by the wind. Thus in dry regions the soil may be gradually lost in dust storms. The finest dust may travel for hundreds of miles and when it settles on the ground there is no reason why it should not be moved again with the next blast of wind. Thus there will be a tendency for all dust to be removed from the driest regions, for it will only stay on the ground where the climate is damp enough to hold it. The familiar picture of a desert as a place of bare rock and sand dunes represents what is left when all the dust has been removed. The sand itself, however, may be blown about and travel considerable distances, doing great damage to the remaining rocks, particularly those within two or three feet of the ground. (In a sandstorm the larger particles of sand are not raised to any great height.)

Diagram of a wide valley with paired river terraces on both sides of the river. These were probably formed when the sea was higher than it is now and the river meandered over a wide plain without down-cutting. Each lowering of sea level allowed the river to cut down to that level and then cut sideways, so producing a new and lower flat valley floor (shown by a different color).

Perhaps the most obvious and the most important way in which material is removed from rocks is by the action of water. Within the soil there is a constant seepage of rainwater down into the ground, and by this means any soluble material may be slowly removed. It may penetrate deep into the ground, where some of the soluble con-



A meandering river showing the banks on the outside bends liable to erosion, and the other side of the stream depositing new alluvium. A meander may become so extreme that the stream cuts across the narrow neck, leaving what is known as an ox-bow lake. One is shown above.

tent may be deposited in the crevices in the rocks, and it may pass out of the ground again through springs into rivers. Most rivers are supplied by such water which has been through the ground and picked up some mineral matter in solution, and each river will pick up a little more in its course towards the sea, because it is continually flowing over rock. In this way even the clearest river carries a considerable load of dissolved matter down to the sea, and in the course of ages this process has made the sea salt. But salt is not the most abundant material to be carried down by rivers; it is merely the part which tends to stay in the sea without being removed. More important are the dissolved products of limestone, which will be discussed later in this chapter.

The sediment which rivers carry in suspension is more obvious than the load in solution. The sediments are sometimes very greatly

increased during times of flood but, of course, the amount of sediment depends on the river flowing along an easily eroded river bed. Throughout the stream's course small particles are being picked up, carried, moved around by the turbulent water, deposited and then picked up again; the larger particles, on the other hand, are only moved in times of the most violent floods. In flat plains, if rivers cannot cut downwards they cut sideways and so wind about or meander. While cutting into one bank of a bend they deposit on the other. OX-BOW LAKES are sometimes formed in the course of meandering. Where the water overflows the banks of the rivers in flood time, sediment is deposited along the floor of the valley and these deposits are together known as ALLUVIUM. They may be preserved for hundreds of thousands of years. But in the course of time the valley is either filled up or, more usually, cleaned out and deepened; then this material is transferred to the sea. Thus, although we may know of many deposits formed on land, few of them escape ultimate transport to the sea.

A river system is sometimes said to pass through stages of youth, maturity, and finally old age. In the early stages a rapid stream will tend to cut downwards, causing deep valleys, gorges, waterfalls and cliffs. In a state of maturity, the landscape is more subdued; it could nevertheless consist entirely of hills and valleys. Finally, in the stage of old age, the stream has cut down to what is known as BASE LEVEL, that is to say, the level of the sea or some lake below which it cannot cut, and at which level it will slowly cut sideways and give rise to a plain. Plains will extend and get flatter until, by some new earth movement or change of sea level, the land may again be raised or the sea fall, and the whole river system become rejuvenated; new waterfalls and gorges will form in the lower reaches and these will gradually work up the valley system (as is happening in the case of Niagara Falls). In this way river systems are constantly changing over long periods, sometimes leaving records of their past history in the form of river terraces – or levels preserved in the sides of the valley which show their previous height.

We may assume that so long as there is land there will be rivers flowing down, so that we can hardly visualize rivers beginning from

nothing. The terms youth, maturity and old age then refer to the degree of activity or the power of the stream in cutting down into the old topography. Sometimes a river which has been meandering in a flat flood plain may, on uplift, cut downwards and so entrench the meanders deeply into the ground. This is known as REJUVENATION.

The idea of youth, maturity, and old age in the development of landscape is applicable not only to river erosion but also to the development of deserts, of land under conditions of ice, and indeed to any superficial process which will tend, in the course of time, to reduce the landscape to a low level until further energy supplied from beneath raises it once again or till the sea level falls and initiates a new cycle of erosion.

When considering the removal of rock waste, we must not forget the sea itself, which is not only a reservoir into which the rivers flow with their burden, but an active agent of attack upon the land. There are some shore lines around the coasts where sediment has been piled up as shingle spits or mud flats, so gaining land from the sea. But on most shores the sea is actively attacking the land through the energy of its waves, which are derived from the wind and are made effective by the sand and gravel they contain. This movement, wearing away at the cliffs, detaches large boulders and small particles which are ground up finer and finer in the swish of advancing and retreating waves and tides, and are eventually washed down below the level of wave action. In the general turmoil of the sea, due to tides and currents and waves, sometimes in different directions depending on the prevailing winds, the net result is to keep suspended material moving until it comes to rest out of reach of the more turbulent surface layers of the sea.

Ice is a most important agent in the removal of material. It is limited to certain parts of the earth – high mountains with valley

Impression of the Solar System. The true sizes and distances of the sun and the planets are given in Table 2. The distance of the sun to the outermost planet is 3,670 million miles. The near stars are mostly more than 250,000,000,000,000,000 miles away.

Ice crystals are best developed in snow flakes where they have grown slowly from water vapor in cold air. Many shapes are formed, but all have the same hexagonal symmetry. When water freezes the ice crystals formed are more tightly packed. When snow changes to ice in a glacier the air spaces between the crystals are filled up and some crystals grow larger at the expense of others.

glaciers, and the Arctic and Antarctic – but in these areas it moves immense masses of material. Glaciers are formed by the movement from high ground of snow which has accumulated and become compacted into ice. A sufficiently large mass will flow very slowly down quite a gentle slope. Ice, indeed, behaves like a slow-motion fluid and is strong enough to carry large blocks of rock. In valley glaciers the snow accumulating in the mountains avalanches down into the depressions in the upper parts of the valleys, where in a year many feet of snow may accumulate and be compressed while the small snow crystals grow into large ice crystals. In these upper regions the ava-

lanches bring down rocks, and frost action on the walls of the valleys and on the high cliffs detaches boulders which fall on to the ice, so that all around the edges of the glacier new rock is tending to accumulate. Beneath the ice, too, its movement is detaching loose rocks, and these, sliding over the surface embedded in the ice, act as powerful grinding tools to smooth away underlying rock. In this way valleys are widened and deepened and smoothed, so that the interlocking spurs of a typical river valley are truncated into a long "U"-shaped, trough-like valley.

In Arctic and Antarctic regions so much snow accumulates that the glaciers cover the whole land, mountains and valleys included, forming ice sheets, the two largest of which now cover Antarctica and Greenland. In the Antarctic much of the ice flows straight off the land into the sea and becomes detached as great tabular bergs. In the Arctic, coastal mountains usually confine the great ice sheets as valley glaciers

Icebergs as seen in a Greenland fjord. They have broken off a large glacier and are charged with boulders from it. The water, warmed by the sun, melts the ice at water level. About seven-eighths of the weight of the bergs is below water level (or more, if they contain much rock). The largest bergs float out to sea and are a danger to shipping.

Picture of an atoll, a coral island with a large central lagoon. Most atolls are much larger and more regular than the one illustrated. The diagrams below show Darwin's theory of their formation, assuming a volcanic island to be sinking beneath the sea, and the growth of the surrounding reef to keep up to the sea surface. This theory is accepted today, except that during the ice age most small islands were cut to a sea level then much lower than now, after which coral reefs could grow with the rising waters. This accounts for the large number of atolls and of lagoons of similar depths.

which eventually flow out into fjords. In both areas the scale of this process is enormous. The ice may be thousands of feet thick, and although the ice can hardly be seen to move, the ice cliffs by the sea are constantly breaking off. The large bergs float away, often carrying a heavy load of rock débris. As they drift along they melt slowly, re-

Stage 1

Stage 2

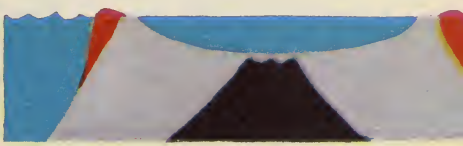
leasing boulders, sand, and the finest mud into the sea beneath. Many ice sheets or glaciers do not reach the sea because melting on land prevents further advance. At this point rock débris is deposited as a terminal moraine. The streams of boulders along the ice, known as median and lateral moraines, will be carried down and concentrated in the terminal moraine, which may form a great dam across the valley if the snout of the glacier remains there for long. If the ice advances, the moraine may be pushed forward and left as a record of its farthest advance when the ice eventually retreats. Long Island (N.Y.) and Cape Cod are examples of such terminal moraines.

Within any glacier, in summer time at least, there are likely to be large streams of melt water. These sometimes flow on the surface and sometimes cascade down crevasses and flow through tunnels on the floor of the valley beneath the ice. They may travel at great speed and themselves erode the valley floor beneath the ice. On emerging from the glacier front these FLUVIO-GLACIAL streams are fully charged with débris, and form a torrent which is liable to remove any available moraine in its path. In Arctic regions the valley floor is permanently frozen and the streams cannot cut deep channels. There these streams usually spread over the whole valley floor, branching and joining, partly because they are so fully charged with material that they are constantly depositing it in their track and so changing course.

*The dumping of rock waste*

The same agents so active in the attack on the rocks and the removal of rock waste also, sooner or later, deposit the waste material to form a sedimentary rock. Deposits on land in the river valleys are attacked

Stage 3



Stage 4

Fossil Foraminifera (forams). On the right is a top view, side view, and section of a nummulite; it is about this size, and lived on the sea bottom in Lower Tertiary times (say 70–30 million years ago). On the left are three views of *Globigerina,* a microscopic foram which lived – and still lives – near the sea surface as plankton.

and removed further down towards the sea in the course of time, as we have already seen. The main mass is eventually carried to the river mouth and deposited in great deltas and along the continental slopes where, beneath the level of wave action, the finer sediments can settle and accumulate.

It used to be thought that beneath this level all was peace and quiet

View seen through microscope of *Globigerina* ooze. This is a deposit found on the ocean floors where little sediment arrives from land and so the dead plankton fall down and are concentrated on the bottom. In this case the commonest fossil is *Globigerina,* hence the name of the soft rock, or ooze, which is largely calcium carbonate.

and the finest sediments could slowly pile up undisturbed. It is now known that this is not so. On the deep slopes of the ocean, where this finer sediment is forming, disturbances cause large masses of sediment to slide down the slopes. A submarine disturbance gives rise to a cloud of water-borne dust or sediment which, being much denser than the surrounding clear water, will rush down any slope, however gentle, to the ocean depths. In this way, much of the sediment which has been brought to the delta fronts and continental slopes beneath the sea may be carried on still farther into the depths of the ocean, where the finest mud may accumulate, possibly thousands of miles from its original source. These density- or TURBIDITY-CURRENTS as they are called, may flow at great speeds, as is known from the exact times when successive submarine cables have been broken. They may carry out much erosion on the way, possibly scouring out SUBMARINE CANYONS. Each particle of sediment may thus have a long story before it is finally deposited and preserved as rock, and even then it may not become hardened for millions of years.

Sedimentary rocks may also be formed in quite another way. So far we have been considering rock waste as a form of powder, sand, or gravel. But now consider the material traveling down the rivers in solution, particularly the limestone material. This calcium carbonate

Microscopic animal skeletons of Radiolaria are made of silica and are less soluble than those of calcite, e.g. the forams. They form radiolarian ooze which is found on some of the deeper ocean floors.

permeates throughout the ocean and is available to all living creatures, some of which use it for their calcareous skeletons. Thus CORAL REEFS accumulate by the steady growth of skeletons of small coral polyps. Shellfish form their shells of this material, and the shells are preserved when the fish die and decay. Where the temperature is high and shallow sea water evaporates, limestone is deposited. In all such forms of limestone deposits the lime material has ultimately come by solution to the sea from rivers, some having originated from decomposing feldspar in the granite at the top of a remote mountain.

Many small animals and plants float in the surface layers of the sea and provide food for CRUSTACEANS, which in turn nourish whales. Those that are not eaten may fall down to the bottom of the seas and oceans when they die. In the deepest oceans, where there is little other sediment to mask the skeletons, various oozes such as GLOBIGERINA OOZE accumulate, formed almost entirely of the skeletons of these microscopic animals and plants. The chalk deposits of Europe were formed in this way, except that the sea was not deep, and the organic sediment in this case was clean because it was far from land and so avoided the admixture of ordinary sands and muds.

Throughout the earth's surface forces are at work decomposing and disintegrating rock, and transporting material to new places where new rock is formed. The rock so formed is invariably sedimentary rock, and this occurs in immense variety throughout almost all the surface layers of the earth. Once it is formed, changes are continually taking place. Percolating waters may deposit more material, causing loose sands to become hard sandstones, muds and clays to become hard shales and slates, and shell banks to become resistant limestones. The general result is the removal of material from above sea level and its accumulation below sea level. Most of it is deposited in shallow seas and along the ocean margins and smaller amounts in the ocean depths.

Reconstructed scene in a coal forest during the Carboniferous Period (say 300 million years ago. In addition to the large trees and plants growing in swampy conditions early insects and amphibians are pictured. The giant dragonfly is *Meganeura*: it was nearly 2 ft 6 in. across.

# 7. Deep forces at work

All the sedimentary processes mentioned in the last chapter derive ultimately from the energy of the sun. If this were the whole story, the earth would long ago have been conquered by the seas, for all material would have been carried downhill and eventually below sea level. But that has not happened because there have been powerful opposing forces coming from within the earth itself. We do not understand them fully, but they certainly derive ultimately from heat energy within the earth, which is probably largely due to NUCLEAR DECAY. Many of these processes are hidden, and affect not only just the surface layers of the earth but the whole internal structure. We can only guess what is happening below. It is better to consider the effects of these deep forces rather than try to describe the processes themselves.

*Volcanoes*

Volcanoes are the most obvious outward signs of great internal forces. Those which are now active are only a very small remnant of the volcanoes of the past. There are several different types, and all of them may occur within even a small area, such as Mexico or Italy. The best-known volcanoes have one main central vent, or CRATER, around which a CONE has been formed. Inside the vent, lava may sometimes be seen bubbling, with steam and various other gases issuing from its surface. Sometimes the lava solidifies and that may be the end of the volcano for the time being. On the other hand it may be the prelude to a new eruption, for the solidification of a crust on top of the lava may cause a devastating explosion if the pressure of the lava beneath it increases.

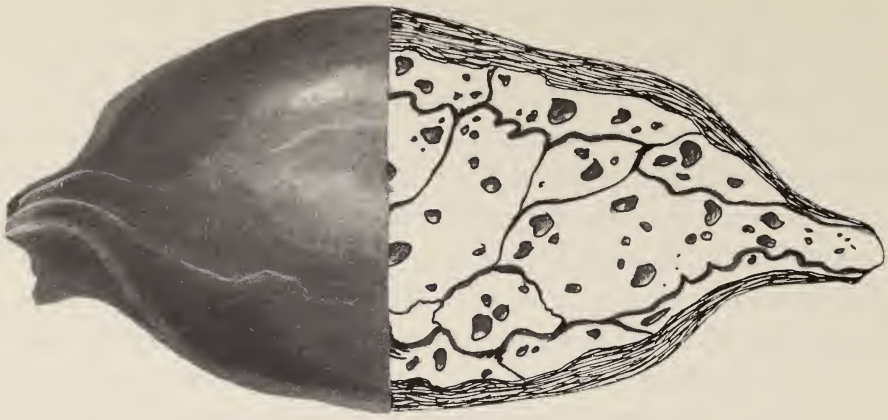
In an explosion of this sort the crust is broken up into small pieces and ejected in the form of dust or lumps of rock. Molten lava is also thrown out as droplets which quickly solidify. Explosive eruptions of

this sort may be repeated at frequent intervals, and a volcanic cone is then gradually built up around the crater. Although much of this rock is igneous, the deposits are sedimentary, because they are formed as ordinary sediments at atmospheric temperatures and pressures. Such VOLCANIC ASHES, or TUFFS may spread out over great distances and even form an important part of deposits in the sea.

Many volcanoes, however, erupt with great lava streams. These seldom flow over the lip of the cone but more usually break out through cracks in its sides, and may run down the slopes very rapidly. Sooner or later they cool and add another layer to the volcanic cone, so that many volcanic cones are formed of both igneous lava and sedimentary ashes. On formation they are subjected to rapid erosion, often accentuated by the heavy rain which follows the cooling of steam from the crater.

Sometimes violent eruptions send forth gas laden with incandescent spray or dust, and many volcanic deposits from the past which were at first thought to be lavas may in fact be consolidated incandescent dust desposits. The main difference between these and lava is that in lava there is a great deal of gas as bubbles within the liquid,

The man is trying to interest the boy in a remarkable mountain which stands out from the surrounding country because of the more resistant rock. This was once a volcanic neck, from around which the softer volcanic cone has been removed.

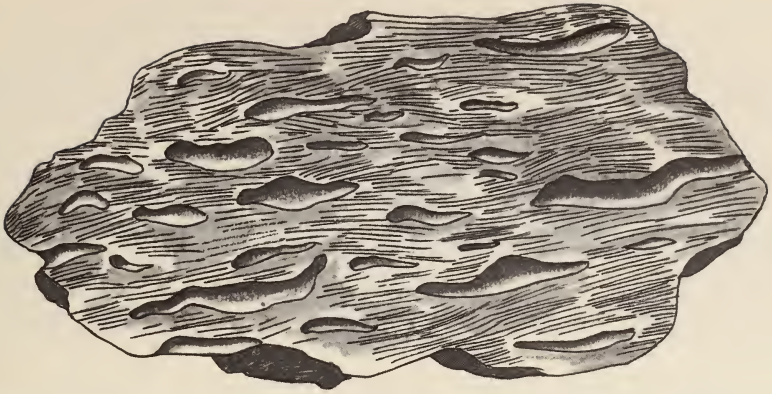


This illustration of a volcanic bomb is half cut away to show that the lava, of which it is formed, is full of holes (vesicles). The twisted end was formed when a small piece of molten lava was thrown into the air in a volcanic explosion. The release of pressure allowed gas to separate as bubbles in the lava, forming the vesicles. It cooled during its flight and landed as an ash fragment or "volcanic bomb".

whereas droplets of liquid within a hot gas may form an incandescent dust. Any lava at first contains a great deal of gas in solution, which is liberated on the release of pressure. This in fact is the actual cause of volcanic explosions.

Volcanoes with lava composition similar to granite are usually the most violent, but they are not the largest. The largest ones usually emit basalt and have little explosive activity. Such volcanoes are known today in the Hawaiian Isles, where only the tops of great oceanic volcanoes appear above sea level. These are formed almost entirely around central vents which frequently pour lava down their slopes. Basaltic lavas appear to be able to flow greater distances and are alto-

Three volcanic craters appear to have erupted about the same time, so giving three lava flows. (From the Puys district of France.)



Fragment of volcanic lava in which the elongated vesicles and the pattern in the rock itself all show the main direction of flow when the lava was fluid. Vesicles which appear as elongated cavities were formed when the lava was erupted and the gas originally in solution separated into bubbles which became frozen in the rock.

gether more fluid, with the result that larger areas are covered.

In times past there have been tremendous lava floods, known as PLATEAU BASALTS. The Columbia Plateau in the western States was built up almost entirely of great floods of lava. It covered an area of perhaps half a million square miles and reached several thousand feet in thickness, each individual flow being 20 to 100 feet thick. Flows of this magnitude must have come from great cracks or fissures in the earth's surface. Other examples well known from the past are the Deccan Traps of India and the more recent Icelandic lavas.

Beneath every eruption visible at the surface there is deep penetration of igneous material within the crust. Some of the greatest eruptions are due to cracks forming in the earth's crust, which allow basaltic lava to flow up from great depths. When these cracks are filled with sheets of solidified basalt they are known as DIKES and SILLS. If they cut across the surrounding rock structures, they are dikes. If they split open the older rock layers and flow in between them, they are sills. Both dikes and sills are known to be associated with regions of igneous and volcanic activity.

*Plutonic processes*

We can observe volcanic activity at the surface of the earth, but we can only guess at what is going on below. Fortunately there are

Diagrammatic section through the earth's crust to show an ideal intrusion of granite into flatlying sedimentary rocks. The granite magma has come up a central vent and spread out between two strata, doming the overlying beds. Such an intrusion (which does not in general cut across the country rocks, i.e. is concordant) is known as a laccolith. It might be a few miles across.

places where much uplift and erosion has revealed very deep structures, and we can learn something from these. In many parts of the earth's crust there are great granite masses known as BATHOLITHS. It was long taken for granted that granite solidified from a MAGMA, penetrating the country and forming immense INTRUSIONS. Some problems connected with granites have already been referred to in Chapter Two.

In the first place their volume itself is so enormous that it is difficult to see what has happened to the rock which previously occupied their

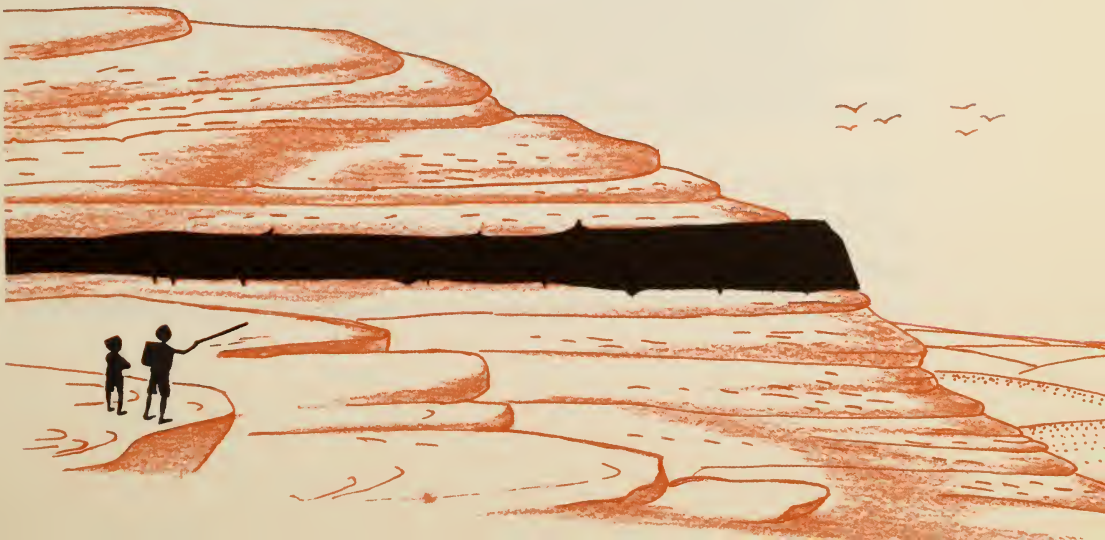
The man is pointing to three dikes in the cliff opposite. Dikes are sheet-like intrusions of igneous rock which cut across the layers of country rock (i.e. are discordant). In this picture they are seen in section and must be imagined to have extended towards and away from the reader.

present space. In some cases there is evidence that the granite has pushed aside the surrounding rock, but in others there is no such evidence. The earlier rock has been simply cut across and completely lost where the granite now is. This is sometimes due to a process of STOPING, by which the granite magma has come up from beneath and surrounded the rock, which, being much denser than the granite magma, has then sunk down into the magma reservoir. Here and there great blocks of rock have been "frozen" in the granite as though, in the act of falling, their descent was arrested as the magma solidified.

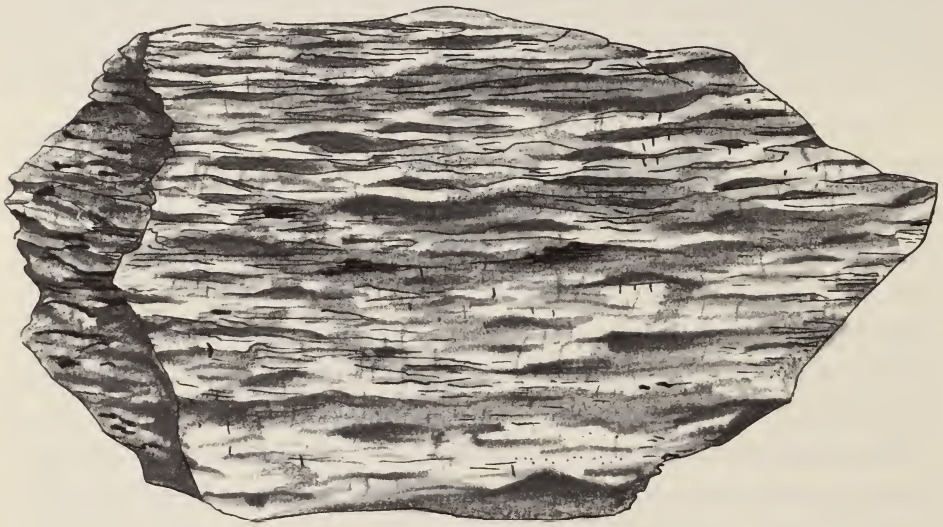
There are other cases where granite seems to have formed out of the pre-existing rocks by a sort of solid transformation. This may be demonstrated by the continuation right through the granite of "ghost" structures similar to those found on either side of it. Here and there it can be shown that the large feldspar crystals, so characteristic of the main mass of granite, appear as outposts within the sedimentary rocks, and gradually increase in abundance, showing a gradual transition from sedimentary rock to granite.

The changes which must occur in the transformation from sedimentary rock to granite are many and complex. They appear to take place by a sort of diffusion of mobile atoms among the solid material, and sometimes the whole change takes place without melting. This seems to be characteristic of some of the deepest granites. But when the process continues, in the melting stage matters become consider-

In this picture the dark layer is an intrusion of igneous rock which has penetrated the nearly horizontal strata. It must be imagined as a section of an extensive flat-lying sheet of rock. Such a flat intrusion (which does not cut across the layers of country rock and so is concordant) is known as a sill.



ably more complicated, and a mixture of altered solid and newly-formed liquid known as MIGMA may form, possibly move to a new position in the crust, and solidify as a MIGMATITE. If the melting had been complete a magma would have formed, giving rise to normal igneous rocks, and we should not know its source. Granitic rocks may thus have been formed by solid change or metamorphism, by



Hand specimen of gneiss (pronounced "nice") – a metamorphic rock formed at great depth. It shows typically irregular streaky layers due to strong earth movements. Gneisses are usually like a kind of squeezed granite but many gneisses have nevertheless formed from sedimentary rocks by granitization.

solidification of a magma or of some intermediate migma. We should note, however, that granites are nearly always associated with regions of the earth's crust which have been subjected to some compression. All appear to be formed at depth and are not obviously related to any large-scale volcanic activity near the surface.

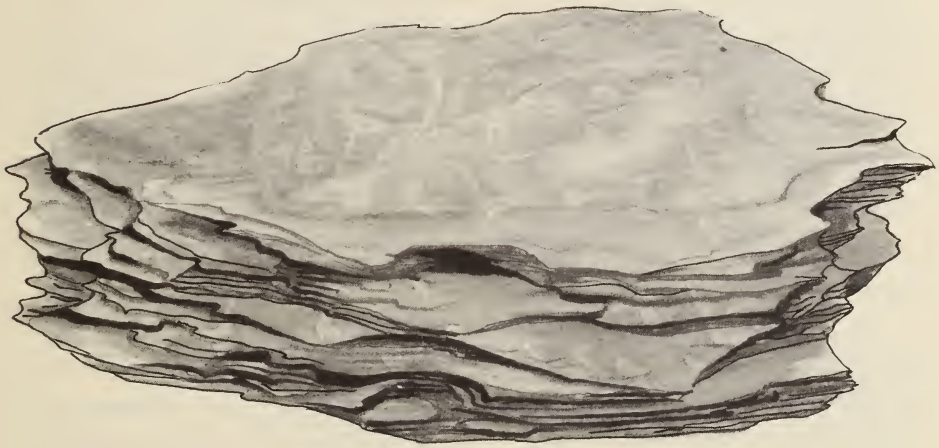
*Metamorphism*

The sort of transformation which produces some granites without passing through a fluid stage is a rather special kind of METAMORPHISM known as METASOMATISM, or change of body composition.

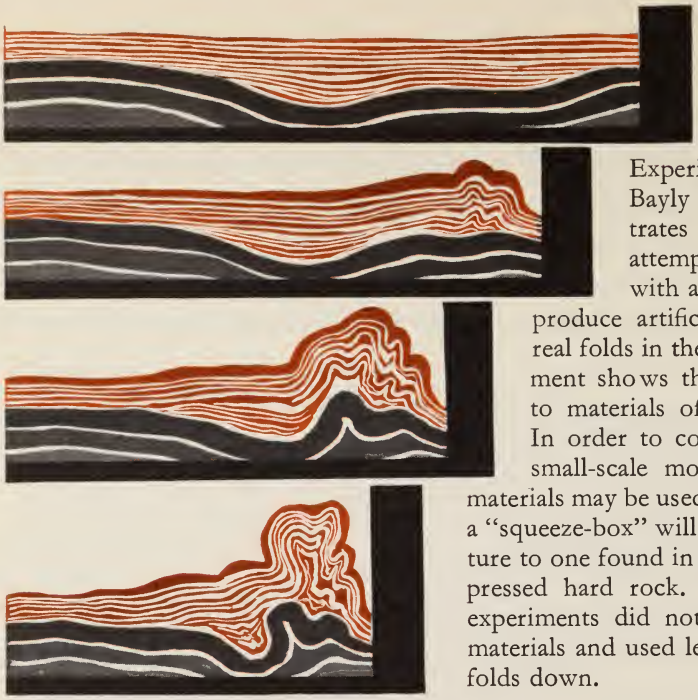
By far the most common and important kind of metamorphism, however, involves not a change of composition but a recrystallization of the rocks, which may at great depths lose all similarity with their original form.

When sedimentary rocks have been deposited one on top of the other to a great thickness, the deeper layers become hardened and changed. This may happen in various ways, owing to percolating solutions and recrystallization. Such changes which take place without much rise in temperature are known as DIAGENIC CHANGES. As the load and the temperature increase with depth, the amount of change may be quite marked. Completely new minerals may appear, very often as large crystals, until, at very great depths, rocks not unlike granite may be formed. Increasing depths produce changes, ranging from the ordinary hardening of sedimentary rocks near the surface through a weak metamorphism, to complete recrystallization at great depth. This final stage is known as plutonic metamorphism.

The best-known metamorphic rocks are, however, due to movements as well as to great pressures and temperatures, and they are found where the earth's crust has been compressed. These regions



Hand specimen of slate. It has a tendency to split in one direction (known as cleavage) because the very fine grain of the rock is arranged that way. The rock was probably originally a shale or mudstone, deposited in layers, but strong earth movements have caused the new cleavage direction quite independently of the original stratification. The latter can rarely be seen in a hand specimen.



Experimental folds, after Bayly Willis. This illustrates one of the early attempts to experiment with a "squeeze-box" and produce artificial folds similar to real folds in the rocks. This experiment shows the irregularities due to materials of different strength. In order to copy hard rocks in a small-scale model only very soft materials may be used – thus fluid mud in a "squeeze-box" will give a similar structure to one found in many miles of compressed hard rock. Some of the early experiments did not use weak enough materials and used lead shot to hold the folds down.

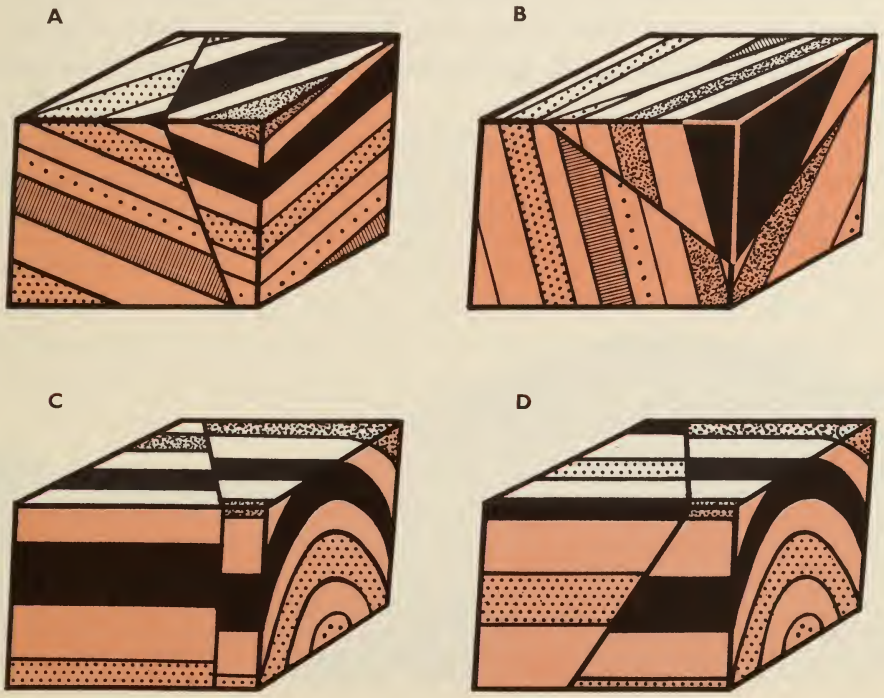
cover vast areas, usually in long belts 100 miles or more wide and many hundreds of miles long, that have evidently been squeezed. The original sedimentary layers have been folded and contorted in many ways and the original nature of the rock has been completely altered. New minerals have appeared, giving rocks known as GNEISSES and SCHISTS. A gneiss is rather similar to a granite but very much squeezed and often banded and layered, while a schist has rather flat-shaped minerals such as mica, or elongated dark minerals such as HORNBLENDE. These rocks could have been formed from ordinary sandstones and shales. Limestones will change to marble, while shale may change to slate.

Chapters Eighteen and Nineteen consider some of the rock structures characteristic of FOLD BELTS. It is quite clear that much wider areas of flat-lying rocks have been compressed into these relatively narrow belts. Those parts which have suffered COMPRESSION have been lifted up as a result of squeezing, and it has been shown in Chapter Five that uplift must be compensated by the pushing down of the mountain root. New mountain belts are therefore due to a local thickening of the earth's crust.

Newly uplifted mountains have steep sides, and this often results in collapse or a sliding down the slope. Within fold mountains the horizontal movements are sometimes so great that huge slabs of rock, many miles long and thousands of feet thick, may be pushed across the surface and possibly slide down the slope of a rising mountain, almost like a surf-rider on a wave. Such slabs are called THRUST MASSES, NAPPES, OR SLIDES.

There is little difficulty in identifying these compressed parts of the crust. If compression alone has taken place, the earth must have been growing smaller and smaller, but it is quite clear that some areas show EXTENSION or stretching. Extension structures, for example widespread small faults, seem to be spread out more evenly over

Block diagrams showing some different kinds of fault. A fault is a rock break with movement. A is a normal fault and B a reversed fault, though it is impossible from the diagram to tell which way the fault has moved. In C and D the fold has been cut by the faults, so it is possible from this to tell the movement, which in C was horizontally along the fault (strike slip) and in D was up and down (dip slip).

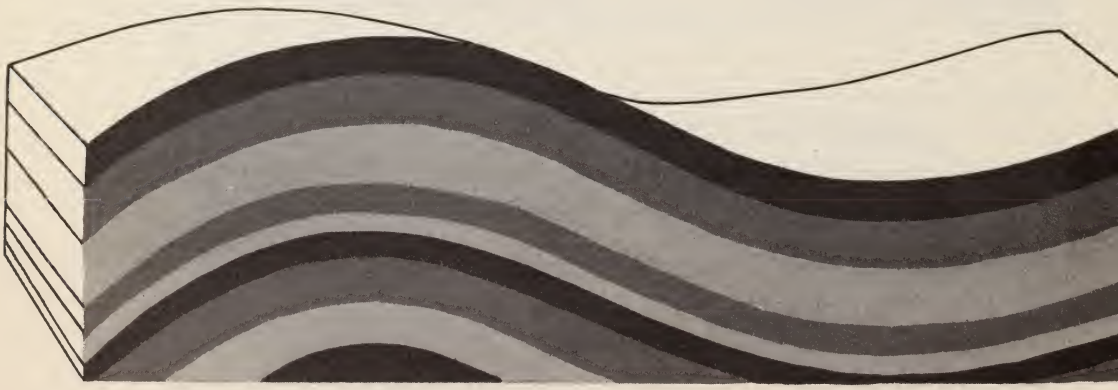


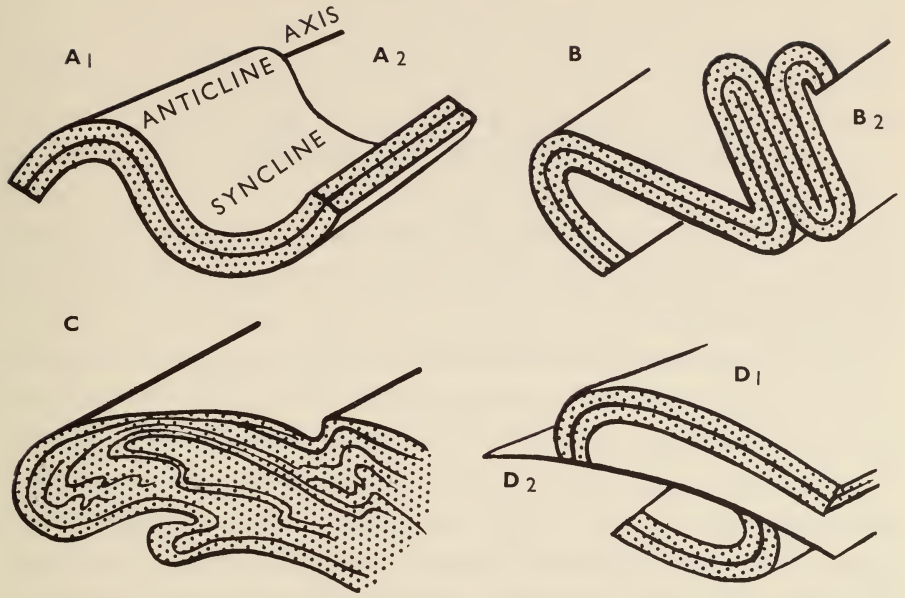
the crust; compression is concentrated in mountain belts. Rock structure has been studied in great detail in coalfields. Some are cut by a network of innumerable small faults, most of which indicate some horizontal stretching of the crust. Another sign of extension is in the DIKE SWARMS which give rise to the great plateau basalts that have already been mentioned.

The extension structures so far discovered in the earth's crust cannot compare with the compression structures for dramatic effect, though it is possible that beneath the oceans huge gaps caused by extension have been filled up with basalt and concealed by later sediment.

There is another sort of structure in the earth's crust known as a STRIKE-SLIP FAULT. This is a great crack, on each side of which the crust has moved horizontally in opposite directions. Perhaps the best known of these is the San Andreas Rift of California. Here, over a length of many hundreds of miles, a great system of cracks or faults in the earth's crust extends up the Pacific coast, and at times the rocks on the west side have slipped to the north and the rocks on the east side to the south. These movements have not only caused the displacement of fences, roads and railways, but have been accompanied

Block diagram of symmetrical anticline and syncline. Such regular folds are the result of layers of sedimentary rocks being compressed in one direction only, so shortening the earth's crust a little in that direction. Less regular folding may take place when the rocks are squeezed more tightly (compare illustration on pages 90 and 93) or when the rocks are not so uniform to start with.






Diagrams to show some different kinds of fold. In each case regular sedimentary strata are folded to give the following structures: A 1, symmetrical anticline; A 2, symmetrical syncline; B 1, overturned anticline; B 2, isoclinal folds; C, large irregular recumbent fold; D, recumbent fold (D 1) cut by thrust fault (D 2). Both C and D may result in the movements of rocks over great distances, when they are known as nappes.

by, and indeed caused, great earthquakes, which were the direct outcome of the breaking of the rocks along the fault. It is quite clear now that earthquakes are almost entirely due to such great crustal fractures or faults. Not all of them are due to horizontal movements, but strike-slip faults are more common than used to be suspected. There are important strike-slip faults, for instance, in New Zealand, the Middle East, and Scotland – all of which can be identified by finding the same structures on each side apparently displaced, sometimes by many miles.

We have evidence, then, of different kinds of movement. In some places two blocks have come against each other and squeezed up a strip of the crust into a mountain chain. In other places extension structures show that the crust has drifted apart or thinned slightly. It is not surprising, therefore, to find other parts of the crust where two

adjoining blocks appear to have moved sideways in opposite directions. The various structures which we see may be partly the results of gigantic blocks moving in relation to their neighbors. Any of these movements may cause earthquakes, from which their position may be determined. All of them indicate that deep within the earth's crust some plastic or fluid motion must compensate for the movement of blocks at or near the surface. We have here a hint of "TECTONIC TRANSPORT", an altogether more powerful transport than that due to surface forces.

The movements in the earth's crust at any time are concentrated in active regions, known as MOBILE BELTS. Zones of compression, or mountain building, are known as OROGENIC BELTS. In contrast to these, the areas between are stable for a time, when the only noticeable movements may be slight warping, uplift, or sinking. These appear as the stable blocks of the earth. But, as we shall see later, even the stable areas have not always been stable and the movement pattern in the earth's surface changes from time to time.

The cause of these movements has not yet been explained, and it is one of the most difficult, yet most fascinating, problems in geology. One possible solution is that a sort of deep structural circulation, on a much slower and grander scale than that of the atmospheric circulation above the surface, takes place within the mantle of the earth, caused by heating beneath it and cooling above, so forming a giant CONVECTION system. It has also been suggested that most of the changes in the earth's crust could be due to cooling and the resultant CONTRACTION. A sort of pulsating mechanism, due to alternate heating and cooling of the earth, has also been suggested. Any satisfactory explanation must not only account for the various complex structures at the surface of the earth but must also fit what is known about the physical properties of the deep interior. One thing seems certain – that the energy for the deep forces working in the earth is due to the production of heat by radio-activity within the rocks and the cooling by loss of heat into space. You may regard the earth as a kind of heat engine, churning away at the depths and continually turning up new material at the surface for the attack of wind, water, and ice.

# 8. The geological cycle

The last two chapters have shown something of the struggle between the surface forces and those in the depths of the earth, each tending to undo the work of the other, thus keeping the surface of the earth in a state of continuous activity – of uplift followed by erosion. This gives rise to what we know as the GEOLOGICAL CYCLE.

In the course of the geological cycle each rock may in turn be formed from a previous one, a process known as the ROCK CYCLE. Chart Two shows how a rock of any type may be weathered and disintegrated, and its débris form a new sedimentary rock. This may in its turn be consolidated, uplifted, and eroded, or it may be buried deeply and be changed into some kind of metamorphic rock. The metamorphic rock in its turn may be uplifted and eroded, giving rise to yet another sedimentary rock; or it may be buried to very great depths, where hot solutions from the earth's interior invade it and turn it by stages into a fluid. In such a case an igneous magma would be produced, and if this were to find its way nearer the earth's surface it would solidify and form an igneous rock. Each igneous rock represents a new start in the rock cycle, and it may not be possible to tell where the original material came from. Once formed, mineral grains are often incorporated in one new rock after another. Quartz crystals, for example, crystallizing in a newly formed granite, may be washed away from the distintegrating granite as sand grains. These may be carried to a sandy deposit and so form a sandstone, which itself may be eroded to form another sandstone. Some mineral particles may thus have passed through many cycles. The roundabout of uplift, erosion, transport, deposition, CONSOLIDATION and uplift again, goes on and on indefinitely.

Where and when do these changes take place? Hills are eroded and their dust is removed by wind, streams, or ice. Mountains are gradu-

ally worn away and their rocks dispersed over the surface of the earth. The deep forces, on the other hand, move the crust so as to concentrate structures, usually in long narrow belts or fold mountains, fault belts, rift valleys, coast lines, and strings of volcanoes. Thus the surface forces spread material all over the surface of the earth while the deep forces focus their power on definite mobile areas.

Sediments are not spread quite indiscriminately over the surface of the earth, for great thicknesses of sediment accumulate in the limited areas of the geosynclines. The geosynclines represent great concentrations of sediment – many miles thick – in deltas, along continental shelves, or in depressions bordering mountains. It is still puzzling why sediments brought down in rivers from mountains should not disperse evenly over the sea floor but collect at particular places where the earth's crust sags to accommodate them. Is the sagging due simply to the weight of the sediment, or does the sediment collect where the earth's crust has made space for it by sagging? Whatever the explanation, geosynclines are an outstanding fact of geology. Their ten or more miles of sediment may be built up in 20–100 million years, which is only a short part of geological time. Yet if all the sediments formed throughout most of geological time were spread out evenly over the whole earth the average thickness would be about one mile.

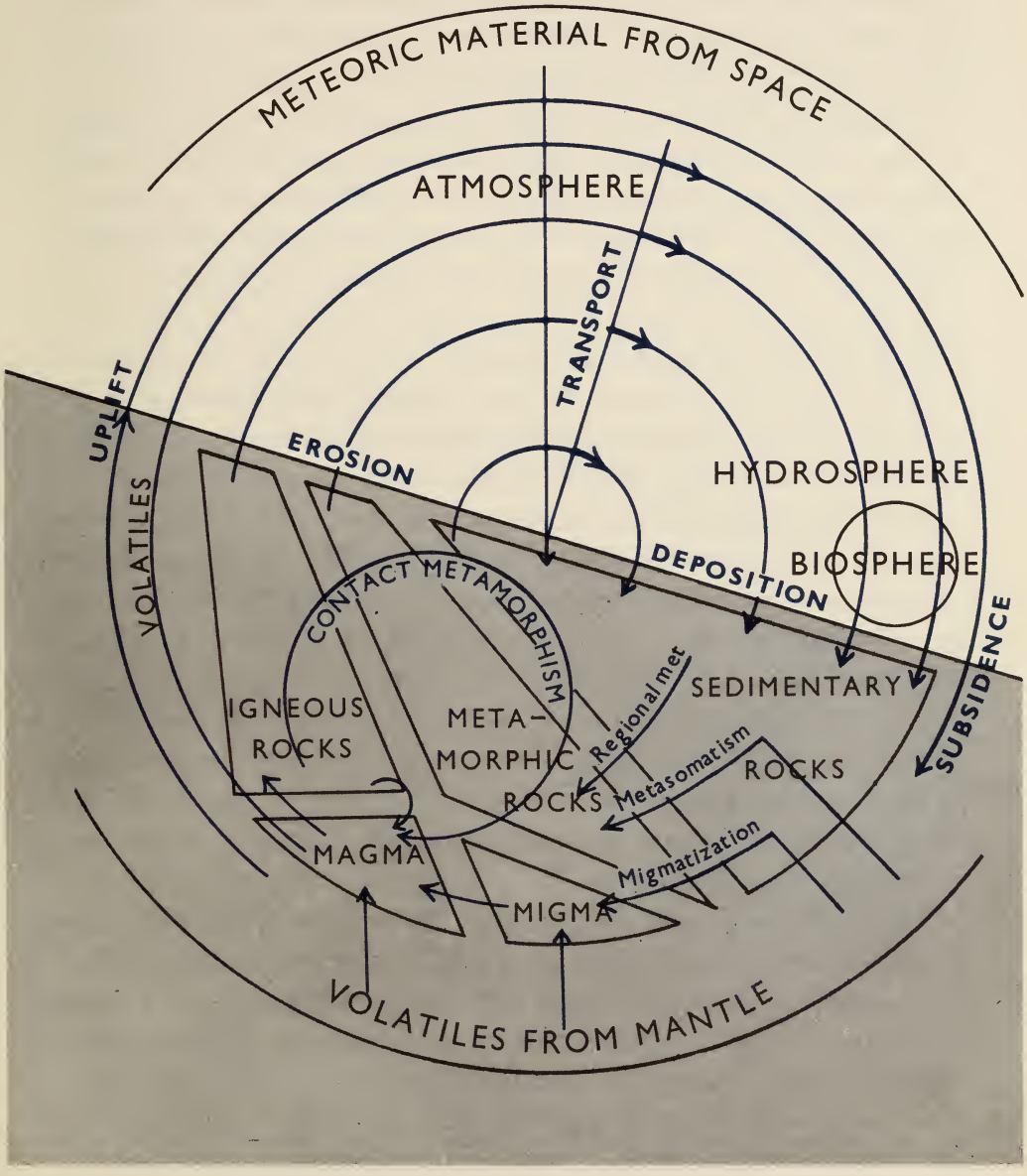
Geosynclines are often folded up into mountain chains, the areas where they occur apparently being susceptible to compression by the deep forces. These areas are called mobile belts. The folding of the geosyncline may be the continuation of some earlier movement, or there may be another explanation. If much of the thick sediment has not been consolidated, the newly formed geosyncline is a belt of weakness in the earth's crust and therefore the most likely part to give way under compression.

Whatever the cause, the result of squeezing a typical geosyncline is

The geological cycle refers to the repeated erosion, transport, and deposition of rocks, followed by their consolidation and possible folding, metamorphism and uplift, sometimes with igneous activity. The diagram indicates some of these processes, more details of which may be found by reference to the glossary and index.

# GEOLOGICAL CYCLE

CHART 2



to produce great fold mountains with extraordinarily varied structures. These are the well-known FOLDS and FAULTS (great THRUSTS, slides and WRENCHES), with metamorphism and igneous intrusions at depth, and volcanoes and earthquakes at the surface. All these are typical of a mobile belt, but not necessarily all found at any one place and time.

In a fold belt such as this the surface layers of the earth are bound to be thickened, for the sediments are squeezed both upwards and downwards, the heights being supported by the deep "roots", and it is in this way that most mountain chains must have been formed. So the creation of new mountains, or OROGENY, from geosynclines is an important part of the geological cycle. Moreover, new mountains may be built up beside old ones, perhaps from the remains of the old, so that many cycles may in time affect whole continents.

*Geological revolutions in North America*

If we work out the history of any continent from the study of its rocks and their structures, we generally find that the geological cycle described above has affected each part of it at one time or another.

In North America, for instance, the mountain chain extending down the west coast and continuing in the Andes of South America is one of these complicated mobile belts. It has been active through the last 400 or 500 million years. During that time, and particularly during the last 200 million years, there have been several distinct cycles. Only about 140 million years ago there was orogeny with metamorphism and igneous activity in the Sierra Nevada (the Nevadian orogeny). The débris from this was carried westwards into the Pacific Ocean and eastwards into the American continent, to form new thicknesses of sediment.

About 70 million years later, when the Sierra Nevada had been worn down and was flanked by new geosynclines, new compression folded the Rocky Mountain chains and raised a new mountain area to the east of the Sierra Nevada (the Laramide orogeny). Erosion followed, covering the Great Plains of North America with sediment up to 10,000 feet thick, and supplying the Mississippi River with the sediment which has accumulated in its delta. The area covered by the

delta stretches both inland and out into the Gulf of Mexico, and it constitutes a new geosyncline at least 30,000 feet thick.

Possibly about 30 million years ago there was another revolution, as the culmination of the geological cycle is called. This time the rocks of the Greater Antilles, south of the Gulf of Mexico, were folded and uplifted, as were parts of the Western Cordillera, or western mountains of North America. During this time the volcanic activity which was creating the plateau basalts of the Columbia River and Snake River regions reached a climax, and volcanoes down the whole chain into Mexico displayed their greatest activity.

Finally, perhaps within the last 2 million years, movements which folded the rocks of the west coasts of California (movements which are still continuing) produced structures of great importance to oil geologists (the Santa Barbara orogeny). Movements along the San Andreas Rift and GEYSERS in Yellowstone National Park are just two signs of present-day activity.

This is only a part of the long and complex history of the Western Cordillera of North America. On the eastern seaboard lies another great fold belt – the Appalachian Mountains. Their growth ceased something like 200 million years ago, and the structures formed during the 300 or so million years preceding this have been preserved. A great belt of metamorphic rocks stretches from Maine to Georgia (south of New York it is known as the Piedmont). It is flanked to the west by the fold mountains of the Valley and Ridge Province. Among these metamorphic rocks there are relics of Precambrian metamorphism of over 600 million years ago, but for the most part the rocks were formed either during the Taconian orogeny, about 440 million years ago, or the Acadian orogeny, about 360 million years ago. The mountains of the Valley and Ridge Province were folded in the Appalachian orogeny about 230 million years ago. This ancient mountain belt – or at least the latest folded margin – appears to extend to the south-west in the visible Ouachita, Wichita, Arbuckle, and Marathon mountains by the Mississippi plain, while other mountains are thought to lie beneath the sediments of this plain. To the north-east the same belt passes through Canada to Newfoundland.

From the region of the Great Lakes still more ancient metamorphic rocks extend northward throughout most of central and northern Canada. This is an area of low-lying country with smooth rounded contours and no obvious mountains, and geographers and geologists alike refer to it as the Canadian Shield owing to its similarity to a shield lying on the ground. It is believed to extend beneath the sediments of the middle part of North America where later rocks, practically unfolded, rest upon it in no great thickness until they plunge down to great depths beneath the geosyncline of the Gulf of Mexico. Flat-lying rocks resting on an eroded shield are called a PLATFORM; such rocks fill the area bounded by the Cordillera to the west, the Gulf and Marathon Mountains to the south, the Appalachians to the east and the Canadian Shield to the north. On closer inspection the Canadian Shield turns out to be not just one vast expanse of metamorphic rocks but a whole series of ancient mountain structures lying side by side, worn down to the roots, and having a common metamorphic character. Adjacent fold belts continue right into the center of the shield, roughly parallel to the Appalachians, and getting older inwards – possibly with intervals between their formation of hundreds of millions of years. All of them are Precambrian – that is, more than about 600 million years old – and the oldest may be much older.

The structure of North America, then, tells the story of a whole succession of geological cycles. Each orogeny was accompanied by uplift, erosion and far-flung deposition – sometimes concentrated into new geosynclines flanked by volcanoes, and sometimes spread far and wide. In due course the new geosynclines were compressed into new fold mountains at the surface which, on erosion, eventually exposed deeper metamorphic rocks and associated granites. The evidence for a succession of revolutions is now found in variously eroded relics of ancient structures, many at different stages of development, and so the story of the continent is made up of a series of chapters.

The principles of classification of the plant kingdom are similar to those for the animal kingdom (shown on page 195 and referred to in Chapter 16). There is less variety than in the animal kingdom, and it is difficult to decide which kingdom many of the simplest organisms should belong to.

# THE PLANT KINGDOM

CHART 3

| Phylum | Class | | Examples living and extinct* |
|---|---|---|---|
| SPERMATOPHYTA | Angiosperms | *Dicotyledons* | *Flowering plants and trees* |
| | | *Monocotyledons* | *Grasses, palms* |
| | Gymnosperms | *Coniferophyta* | *Conifers*<br>*Ginkgo*<br>*Cordaites* (Carboniferous)* |
| | | *Cycadophyta* | *Pteridosperms**<br>*Caytoniales* (Mesozoic)*<br>*Cycads*<br>*Benettitales* (Mesozoic)* |
| PTERIDOPHYTA | Equisetales<br>Sphenophyllales<br>Filicales<br>Lycopodiales<br>Psilophytales | | *Horsetails (or scouring rushes)*<br>*Extinct* (Carboniferous)*<br>*Ferns: common fossils*<br>*Club-mosses (fossils)*<br>*Extinct* (earliest Devonian land plants)* |
| BRYOPHYTA | Liverworts<br>Mosses | | *Few fossils* |
| THALLOPHYTA | Fungi | | *Not known as fossils* |
| | Algae | *Diatoms* | *Micro-organisms with siliceous skeletons* |
| | | *Green*<br>*Brown*<br>*Red*<br>*Blue-green* | *Seaweeds, waterweeds, known mainly from those which secrete a limey skeleton, e.g. Collenia* (Pre-Cambrian)* |
| | Bacteria | | *Important as geological and chemical agents* |

# *Part 3*

# THE STORY OF THE EARTH

## 9. The shaping of the earth

*Uncertain beginnings*

It would at first appear to make little difference to geologists what view is held about the origin of the earth and the solar system, but it does in fact have a very important bearing on many of their problems.

Astronomers tend to believe nowadays that the solar system – that is, the sun, the earth, and all the other planets, with their satellites – came into being some 5,000 or more million years ago by condensation out of some vast spinning cloud of gas. It is thought that on cooling this hot cloud of gas would give rise first to liquid, and then very rapidly to solid particles, mostly in the form of very fine dust. Some quite large lumps, possibly up to several miles in diameter, may have been formed later. These together circled a central embryo, the sun, smashing against each other in the general chaos, sometimes breaking up into smaller pieces, but gradually building up into larger masses. Once formed, large masses attracted many more particles to them by gravity, and so the planets grew from the accumulation of many small masses. This theory, put forward by Otto Schmidt, is held to account for many of the features of the solar system not explained by the earlier NEBULAR HYPOTHESIS of Pierre S. Laplace, by Chamberlin and Moulton in their planetesimal hypothesis, nor by James Jeans's TIDAL THEORY. The new theory involves, however, a gaseous origin in common with the nebular hypothesis, and also shares together with the planetesimal hypothesis the idea that the planets were built up of an aggregate of meteoric bodies. However,

there are still many difficulties.

Table 2 summarizes some features of the different members of our solar system and shows how the planets vary in size, mass and density. It also shows that the earth is peculiar in having just one satellite, which is very much larger in proportion to its planet than is any other satellite. According to the tidal theory the moon was detached from the earth when the earth was a spinning molten mass. It is now thought that the moon must be simply another planet-like body, accumulated from smaller particles, which became captured by the earth's gravitational field. In the same way the meteorites, the ASTEROIDS, and many other bodies belonging to our solar system, probably originated out of this primordial cloud of dust, either directly or as fragments of bodies that collided.

The Moon, because of its small weight – and therefore its small attraction – has lost any ocean or atmosphere which it might have once had. Consequently the surface is completely unaffected by the normal processes of denudation and deposition which we have observed on our own planet. Without winds, water, or ice, most of the active agents of erosion by surface forces are lacking. Only the extreme changes of day and night temperature may have had some effect, breaking up the rock surface of the moon into a fine dust. The face of the moon shows an enormous system of craters which were long thought to be relics of giant volcanoes, the flat areas inside and outside them being vast plains of lava poured out from these craters. Another suggestion, however, is that the craters have nothing to do with volcanic activity but are due to the impact of meteorites or other bodies. This is also reasonable since a few recently-formed meteoric craters are found on the earth. The large flat areas may simply be due to the dust from rock disintegration slowly working its way into all the hollows and smoothing itself out over the surface of the moon. This could have taken hundreds or even thousands of millions of years, for there may have been nothing to disturb the slow process.

According to this view, the lack of air and water on the moon may have given us an opportunity of seeing what our own earth looked like in its early stages, when it was still growing by the bombardment

## TABLE 2 THE SOLAR SYSTEM

| *Planet* | *Average distance from the sun, in millions of miles* | *Diameter in miles* | *Number of satellites* | *Mass, in terms of the earth's mass taken as unit* | *Average density, in terms of the density of water taken as unit* |
|---|---|---|---|---|---|
| Sun | — | 865,000 | .. | 333,400 | 1·41 |
| Moon | — | 2,160 | .. | $\frac{1}{81}$ | 3·34 |
| Mercury | 36 | 3,000 | 0 | $\frac{1}{27}$ | 3·73 |
| Venus | 67 | 7,600 | 0 | $\frac{5}{6}$ | 5·21 |
| Earth | 93 | 7,900<br>7,927 | 1 | 1 | 5·52 |
| Mars | 142 | 4,200 | 2 | $\frac{1}{9}$ | 3·94 |
| Jupiter | 484 | 82,890<br>88,800 | 11 | 318 | 1·34 |
| Saturn | 887 | 67,200<br>75,100 | 9 | 95 | 0·69 |
| Uranus | 1785 | 30,900 | 5 | $14\frac{3}{5}$ | 1·36 |
| Neptune | 2797 | 33,000 | 2 | $17\frac{1}{3}$ | 1·32 |
| Pluto | 3670 | Unknown | 0 | Unknown | Unknown |

*After* C. F. Smart: *The Origin of the Earth*, pp. 28–29 (Penguin)

of meteorites or other masses. If this is so, and the earth's surface at one time resembled that of the moon as we see it now, the differences in the earth are due to the work of our oceans, atmosphere, and earth-movements.

If we imagine the earth as built up of particles which came together, attracted by each other's mass, it might have been quite cold at first. However, the impact of new material and the increasing pressure inside the earth as it grew must somehow have heated up the interior. Even so, this gives a colder picture of the earth than do the earlier

views, according to which the earth began as a ball of molten gas, then became a spinning mass of white-hot fluid, and eventually developed a crust floating as a scum on the surface. Thus we have to consider both "hot earth" and "cold earth" theories of the origin of our planet.

But however the earth was formed, we now know that the present temperature does not depend entirely on what the initial temperature was. This has become clear ever since it was found that heat is generated by minute quantities of radio-active elements when disintegration of the nucleus of their atoms takes place. This may be insignificant in itself, but when the radio-active heat is distributed through much of the interior of the earth and has accumulated for millions of years, it may have had a profound effect on the temperature of the earth. So if the earth began as a hot ball of molten material it probably cooled very rapidly at first, and then, when most of the crust had solidified to form a blanket, it cooled more slowly than it would otherwise have done because of the presence of radio-active material continuously producing heat. On the other hand, if a "cold earth" theory is accepted, then the heat from the radio-active material added to the heat of compression would gradually warm up the whole earth, perhaps even to the extent of melting and expanding the whole of the interior.

The present temperature of the earth is the result of a gain in heat by radio-activity and a loss of heat by radiation from its surface, taking place throughout countless ages, and the net effect today may not depend very much on how it all began. According to the "cold earth" hypothesis, as the earth heated up the denser material would gradually sink down to the center of the earth, and the lighter material would make its way outwards – a process which might still be going on. Steam issuing from volcanoes would have given rise to the oceans, the gases issuing from the rocks would have formed the atmosphere, and the earth's gravitational field, unlike the moon's, would be strong enough to retain them. All this is guess-work, based on general astronomical and physical ideas. What direct evidence is available of the earliest phases of earth history?

The oldest rocks we know are sedimentary rocks. They were probably formed in the sea, which was at a temperature very similar to the temperatures of the warmer seas today. From the evidence of familiar weathering processes today these rocks suggest that there was an atmosphere round the earth very much like that of today. Indeed the whole impression given by the earliest rocks is that conditions were similar to those which are found now at the earth's surface. The surprising thing is that these oldest rocks may contain some evidence of life, and their age may go back as far as 2,500 million years or more. According to some estimates this is about half way back to the beginning of the earth's history, or possibly even to the beginning of the solar system or the universe itself.

Evidently by that time conditions on the earth were suitable for life, and although all the subsequent history recorded in the rocks shows fluctuations in climate and variations in conditions, as far as we can judge there is no evidence of the earth itself cooling or heating. It seems as though its surface had by that time achieved a state of equilibrium between the heat lost and the radio-active heat released. Its subsequent history consists of a series of geological revolutions, upsetting and restoring a natural balance between the deep forces and the surface forces.

*The origin of the continents*

According to one "hot earth" hypothesis the continents began as a sort of scum floating on top of a turbulent liquid. The upward currents would push the scum sideways and concentrate it above the downward currents. However, the materials of which the continents are made have a lower melting point than the materials on which they are thought to rest, so it is unlikely that a continental scum would become established in quite this way. On a "cold earth" hypothesis the continents would separate out as light mobile material from a solid mantle. But before trying to suggest the origin of continents, it might perhaps be better to look at their more recent development.

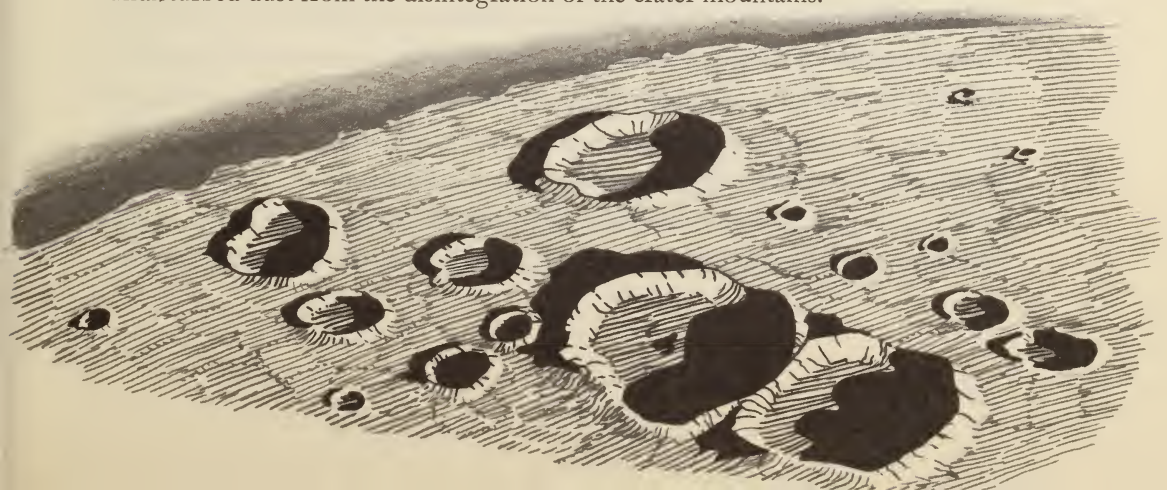
The geological cycle shows a pattern of erosion, deposition, and the formation of geosynclines which were later compressed, folded and

uplifted. These changes, which give rise to great fold mountains lying above metamorphic rocks, seem to have occurred in all the continental areas at one time or another. In fact it is possible that the continents are made up entirely of such relics. It often happens that the continents are eroded, new geosynclines formed, and new mountain belts built up from them, again and again. The process seems rather like digging the same material over and over. There is, however, a steady addition of new material to this cycle, supplied by the volcanoes from deep down in the earth, and once this material has reached the surface it is included in the cycle.

Some believe that the continents may have grown through the development of active volcanoes along their ocean frontiers, like island arcs, very similar to the festoons of volcanic islands which now surround the Pacific coast of Asia. New material is constantly being brought up from below, and although some of it passes out as dust over the earth's surface, most of it will fall very near the site of the original volcano and will then be eroded and deposited in the neighboring seas. This will often help to build up geosynclines. Many geosynclines, indeed, contain a great deal of volcanic material which has come indirectly from deep inside the earth. By the compression of these geosynclines around their margins the continents could grow. In such compression and metamorphism granites and gneisses were added at depth and some of this material may also represent new additions to the continents from beneath.

It is possible that North America has grown in this way, for at

Impression of craters on the moon. Their origin has been suggested as due either to volcanic action or to the impact of giant meteorites, and the flat areas within and between the craters may be the result respectively of lava flows or accumulations of undisturbed dust from the disintegration of the crater mountains.



different periods the mountain belts on the west and east coasts have developed out of geosynclines, and these may well have bordered the open ocean. Because the sediments in these geosynclines were known to have come largely from the sides now bordered by oceans, it was once thought that there must have been continents on these sides when the geosynclines were formed. In other words it was believed that the sediment for the geosynclines bordering the coasts of North America was supplied by great continents that formerly existed where the Pacific and Atlantic Oceans now lie. Nowadays, however, this sediment is regarded as having come from volcanoes uplifted in the surrounding ocean, and not from continents of which there is now no trace left.

This question raises another problem in the history of the continents and the oceans: have they always held their present positions and shapes? The Pacific is, perhaps, different from all the other oceans. It is by far the largest, covering about half the surface of the earth, while the other half, sometimes known as the land hemisphere, consists of the continents separated by smaller oceans.

If we look at this pattern of land and sea we find that the boundary between the land hemisphere and the Pacific Ocean, or water hemisphere, is made up of newly-formed mountain chains with island arcs, and stretches round the west coasts of North and South America, possibly down into Antarctica, around through New Zealand and the East Indies, up along the east coast of Asia through Japan, then through the island arcs off north-east Asia and back into the Aleutian Isles and Alaska. Throughout the whole length of this great girdle of mountains there has been activity at some time or other within the last 50 million years, but in most cases this activity extends much further back in time. Even so, it represents a relatively young feature on the earth's surface, as far as we can tell. It is an area of continued activity, with both earthquakes and volcanoes, where movements of the crust upwards, downwards and sideways, can be observed. It is thus one of the most conspicuous features of the earth's surface.

There is another, rather older, belt which is nearly at right angles to the great circum-Pacific belt, and runs approximately parallel to the

equator from North Africa and Spain, across Europe through the Alps and Carpathians into the Caucasus of Russia, then down by the Zagros mountains of the Middle East, and in a great belt to the Himalayas, where it widens to include the parallel ranges of the Karakoram, Tibet and southern Siberia. This mountain chain, the backbone of Asia, is the greatest in the world. At its eastern end the belt fans out, joining the circum-Pacific belt of East Asia. This east-west belt has been the scene of many geosynclines and their upheavals from at least 200 million years ago, when the great Altai mountains of Asia were formed. Furthermore it has been active throughout the last 50 million years, when the Alps of Europe and the Himalayas of Asia were uplifted.

These two great belts, which are so clearly defined, tend to obscure the relics of earlier ones. In north-west Europe, from Britain up through Scandinavia and far into the Arctic in Spitsbergen and Greenland, there is the Caledonian Mountain system, whose history is very similar to that of the Appalachians in eastern America. Indeed most of the earth's surface can be analyzed into belts of greater and greater antiquity – the earlier being obscured by the later ones, so that the oldest are only preserved in fragments spared by later upheavals.

These great mountain belts stretching over most of the world provide good evidence of compression, or shrinking of the earth's crust. In some cases it is clear that the continents or ocean floors on either side of the mountain chain must have driven against each other for a distance of 50 to 500 miles, squeezing the rocks into folds and many complex structures. If these mountain belts are typical of much of the earth's surface, and if similar ones were formed throughout much of the earth's history, then different parts of the continents must have moved great distances towards each other. It is possible that whole continents moved in relation to each other, so that some of their edges were closer together and others farther apart. This is the theory known as continental drift.

An alternative possibility is that the movements which have folded the rocks are due to overall shrinking of the earth's crust. According to this view, movement causing a loss of space between a continent

and its neighbor on one side could not be made up by a gain in space between it and its neighbor on the other side, as is assumed to be possible in the continental drift theory. This hypothesis has been developed best by HAROLD JEFFREYS.

The two opposing hypotheses of continental drift and crustal contraction have been put forward to explain the movements which must have folded the mountain chains and produced many other features. They have been held in opposition to each other, but they could each have worked at different times and in different places. According to the contraction hypothesis, slow cooling of the earth has allowed it to shrink and so compress the crust. It is more difficult to think of a mechanism strong enough to make continents drift as a whole, but heating deep in the mantle and cooling at its surface may have produced slow, but strong, currents. Such convection currents turning slowly round would carry parts of the crust and mantle along with them, separating some continents and bringing others together.

Until it is known whether or not continental drift has taken place we need not be too anxious as to how it could work. There is no question, however, that movements have taken place, that immense forces have compressed whole tracts of the earth's crust, and that the energy for this work probably comes, in one way or another, from temperature changes in the earth due to heating or cooling.

If the movements on its surface are due to the shrinking of the whole earth, the fold mountains may be likened to the wrinkling of an apple skin when it dries. If, on the other hand, the folds are caused by parts of the earth's crust moving in relation to other parts, the wrinkles would be compensated by splits or openings elsewhere. Large openings, if they occurred, must have taken place under the oceans where they would be rapidly filled up by basaltic material and would be difficult for us to detect afterwards. Many now seriously consider that the earth may have expanded and that the oceans represent the scars where the crust has opened and been filled from beneath. This could explain continental drift without convection currents. On the other hand, some such movement could have simply stretched the crust without splitting it, and there is plenty of

evidence, in the form of widespread but small-scale fractures in the crust, which suggests this. Some have argued against the theory of continental drift because they have not been able to suggest how it could work; others because they consider such a drastic explanation to be unnecessary. Many, however, feel that the evidence is enough to take the possibility of drift very seriously.

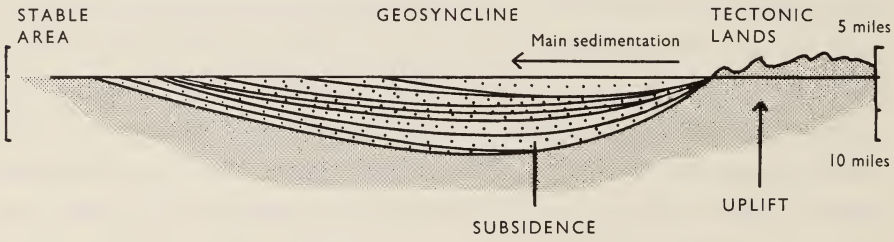
The question will only be settled by searching the rocks and fossils all over the world, and reconstructing past geographies at different times to see how they fit together according to different theories. So far, most observations could fit either hypothesis. The distribution of animals and plants, for instance, is in some ways more easily understood by assuming that some continents used to be closer together. On the other hand it is well known that animals and plants can migrate, or be carried, great distances, and there has certainly been plenty of time for this to happen. The map on page 21 shows the theory of ALFRED WEGENER, who did more than any other to spread the idea of continental drift. According to this the continents of South America, Africa, India, Australia, and possibly Antarctica, which have so many features in common, once formed a super-continent called GONDWANA, which was divided by the opening up of the south Atlantic and Indian Oceans, and whose pieces subsequently separated and drifted apart. Similarly, the North Atlantic may have been formed by North America and Greenland drifting westwards from Europe – all these areas, together with Asia, having once formed another super-continent called Laurasia. However, many who now believe continental drift to have taken place do not agree with Wegener's own reconstructions, for there are many possible alternatives, and certainly do not agree with the mechanisms he proposed.

A suggestion of a different nature is that there has been a PULSATING MECHANISM in the earth, causing alternate EXPANSION and contraction. Some evidence for this has come to light through the study of sea level, which is known to have been higher at times in the past than it is now. At such times there were not so many high mountains, the land as a whole was lower, and a larger area of the earth's surface was covered by water. At other times, when conditions were more like

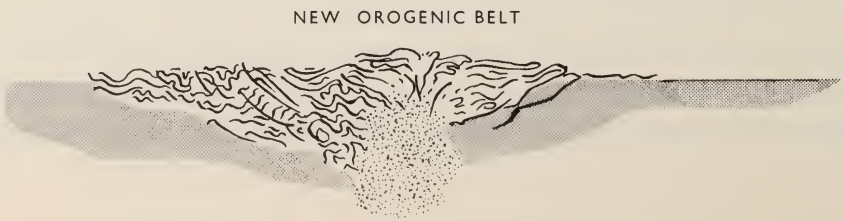
those of today, the seas retreated as mountains rose, only to overflow on to the land again as it was leveled and as more débris began to fill up the seas. Earth history, then, tells of a series of changes between periods of rising and falling sea level, suggesting a pulsating pattern of earth movements.

The study of mountain building all over the world has also suggested to some a series of simultaneous REVOLUTIONS, pulsations, or movements interspersed by quiet periods, throughout the world. However, many earth movements cannot be dated at all accurately, and while it is tempting to fit them into a regular scheme emphasizing the pulsation idea, they also fit in with the idea of continuous movements. It seems more likely that earth movements are taking place all the time, being more active at different places at different times, and any so-called pulsation would be simply an increase or decrease in the average effect. Continental drift may have contributed to the pulsation effect if it took place somewhat jerkily.

But any explanation as to how the earth has behaved must wait until we learn more about the detailed surface history from patient study of rocks everywhere.




Diagrammatic section of a thick mass of sediment known as a geosyncline. The source of the sediment may be an uplifted mountain area, or a string of volcanoes. The geosyncline may be formed on land as a river flood plain, or beneath the sea, or both. The lower diagram gives an impression of a geosyncline compressed by strong earth movements and metamorphosed at depth.



# 10. Past climates

If we could know what the climate was at different places from time to time during the history of the earth we would be able to answer many questions, including possibly those to do with continental drift. This knowledge would also give us a much better background to our understanding of the story of life, especially if we could find out how far back in the earth's history there were climates similar to those we know today. All parts of the earth have been affected by changes in climate at some time or other. Is this due to marked changes in the overall climate of the earth's surface, or have the continents moved about and sampled conditions in various places at different times, or has the raising and lowering of mountain chains brought about local changes in climate?

*The last ice age*

It is sometimes said that we have just emerged from a great ice age, but it is not at all certain that we have yet emerged from it finally. The world climate today still seems to be rather colder than it has

Drumlins are hills made largely of boulder clay and streamlined by the overriding movement of a large glacier. They are typically longer and flatter than the one illustrated, elongated in the direction of ice flow, and with blunt end upstream. They usually occur in groups where large areas of ground moraine beneath an ice sheet have been moulded.

Terminal moraine of a valley glacier, consisting of boulders, gravel, sand and clay mixed together. Such a moraine may accumulate from the various medial moraines and other material brought down by the glacier, at the point where the ice finally melts. A new advance of the glacier may push the whole moraine down the valley. The background scenery is typical of glaciated country.

been through most of the earth's history. Even during the last million years, which include the great ice age, there have been times when the ice has almost disappeared and climates have been far warmer than they are now. Within the last ice age there were alternate glacial and inter-glacial periods, with about six main ice advances, and at least one great inter-glacial period when the climate was very warm indeed. How have we come to know about this?

For many years stories were told in the Swiss valleys of advances and retreats of the ice, some of these quite rapid (over short distances within living memory), and it was clear that the glaciers there had not always been of the same size or extent. It was not until nearly half-way through the nineteenth century, as we have seen in Chapter One, that Agassiz and others realized that their findings could be applied to other parts of the world as well as to Switzerland, and that vast tracts of land, miles from any present glaciers, had been covered by ice at some earlier time. The evidence for this was mainly the polishing and scratching of rocks by sand and boulders in ice, and the widespread deposits which are ancient moraines left by the ice after it had melted and retreated. These deposits are known as boulder clays or TILLS, and TILLITES when they have been solidified and hardened. They were formed both on land and in the sea – on land by the melting of huge glaciers, and in the sea where they were dropped from floating

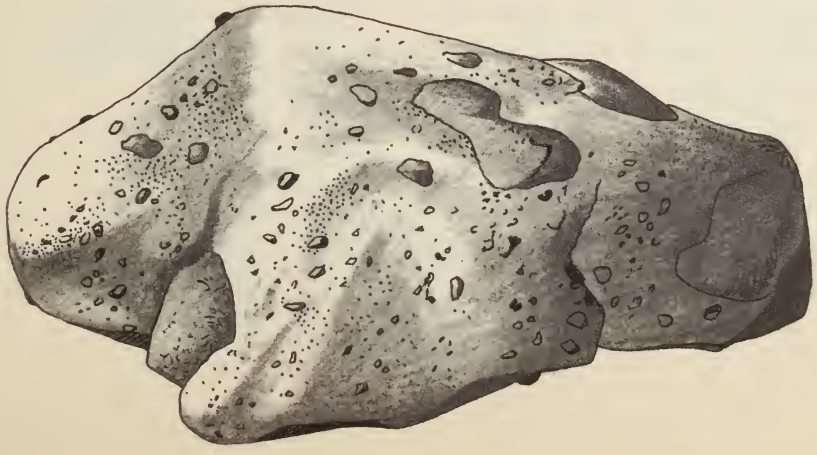
ice broken off glaciers as they reached the coast.

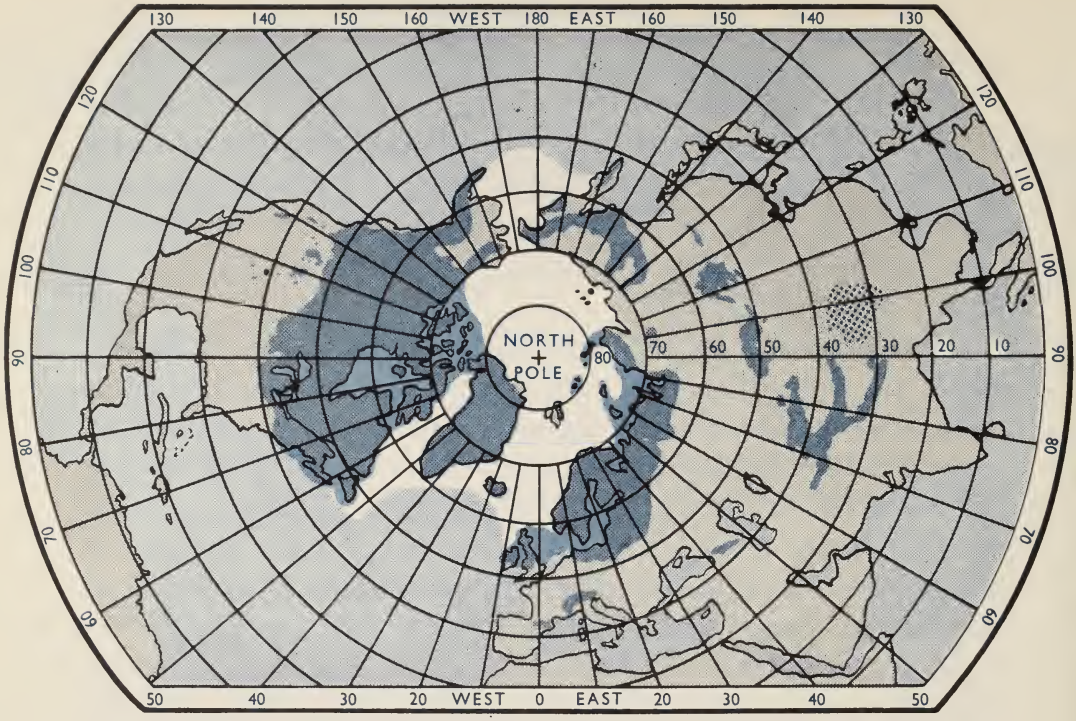
Evidence of this kind was found far beyond the Swiss valleys, over the plains of nothern Europe. It gives a picture of extensive ice sheets spreading out from Scandinavia across the North Sea to England and Wales, across northern Germany into Holland, and across Finland into Russia. At the same time smaller ice sheets radiated from the high mountains of the Alps.

A similar picture became clear to Agassiz when he went to America, where the evidence is even more striking. The thousands of lakes throughout the Canadian shield occupy hollows made by ice action, some of these being hollows ground out of the solid rock by moving ice, and others being due simply to the irregular way in which moraines were laid down. The ice extended far out from a center in northern Canada right down into the United States, where it covered part of the drainage system of the Mississippi.

The evidence for such large ice sheets still remains over much of the land surface, and has not yet been removed by erosion. We also know, from fossils found in some of the deposits formed during inter-glacial periods, that the animals and plants living then were very similar to those of the present day. Even just before the onset of glacial conditions, living things were not so very different from those of today.

Hand specimen of boulder clay. Such a deposit of different sized boulders, pebbles, sand, and the finest clay particles is formed from melting ice whether on land or at sea and the resulting rock is known as a till. Ancient boulder clays may become hardened and are known as tillite. Tillites are amongst the best indicators of past climatic conditions.






Map showing the maximum glaciation at the end of the last ice age in the northern hemisphere. Extent of glacier ice is shown in deep blue. The white areas show the extent of sea ice. The grey stipple was land, the pale blue was sea and the latter was generally less extensive than today being 3–400 feet lower. Modified after R. F. Flint: *Glacial Geology and the Pleistocene Epoch* (Wiley).

All this, then, suggests that the ice age occupied only a short period of geological time, certainly less than a million years and possibly only about half that amount. During that time north-west Europe and the northern part of North America were each covered by tremendous ice sheets similar to those which now cover Greenland and Antarctica, and the ice sheets of Greenland and Antarctica themselves spread far beyond their present position. Elsewhere in the world, too, there is evidence of cooler conditions at that time, for, where it was not cold enough for ice to develop, the changes in climate between hot and cold followed the same pattern. The map on this page shows how far the ice spread over North America when it was at its greatest extent, and that on page 117 the advance and retreat of some of the ice fronts around the Great Lakes, which, as we have already seen, owe

their very existence to the ice. Lakes, indeed, are characteristic of any land which has been recently glaciated, for lakes will not normally develop anywhere unless the natural drainage is deepened or blocked in some way.

In the middle of the Canadian shield and on the high mountains of Norway – thought to be the centers of two great ice sheets – there is little evidence of fluctuations in climate, because the last glaciation removed all evidence of former events. On the other hand, the marginal areas of the ice sheets provide a great deal of evidence of this sort. Beyond the ice front many animals roamed after being driven south by the cold, and at least towards the end of the ice age early man himself appeared, leaving relics often in the form of stone or FLINT implements. Deposits formed between glaciations are found sandwiched between boulder clays, and may be followed once again by further inter-glacial deposits laid down under warmer conditions.

Around the edges of the ice sheets vast river systems developed. The melting ice provided enormous volumes of water which carried silt, sand and boulders in great quantities, often choking up river valleys or cutting deep gorges. Advances and retreats of the ice front are therefore closely bound up with the development of river systems, and it is very often in these river sands and gravels that the fossils

Map illustrating a stage of the ice front (thick line) around the Great Lakes during the Ice Age. The present distribution of the lakes is the result of a complex history glacial erosion and deposition. During this stage the ice sheet (white) extended from the north and dammed up the earlier drainage, forcing the lakes (blue) to drain southwards as indicated. The lakes are known as Dulworth (D), Chicago (C), and Lundy (L).

referred to above are found. The cold weather often killed off great forests, so that soil which had been protected by tree roots was exposed to wind erosion and was carried far beyond the limits of the ice sheets as wind-blown dust, or LOESS, so common in central Asia and the central United States of America. American loess is not easy to identify since wet conditions have changed most of it into a clay.

Some of the most important changes which accompanied the advance and retreats of the ice were the changes in sea level. It has often been said that if all the ice at present locked up in the Greenland and Antarctic ice sheets were melted and added to the seas, the sea level would be higher than it is now by something like 50 feet. The sea level is in fact changing year by year in response to gradual changes in the ice of the Arctic and Antarctic regions. During the ice age the greater volume of the ice caps must have meant a great reduction in sea level, estimated to have been as much as 400 feet.

Such a reduction of sea level, though small compared with the depths of the oceans, would have had a considerable effect on the shape of coastlines all over the earth. Where the sea was shallow new stretches of land would appear, and the weather there would be changed as a result of the rearrangement of land and sea. The changes in sea level also affected the development of river systems. A lowering of sea level allowed rivers to cut deeper channels, and then, when the ice melted and the sea level was raised again, these valleys were filled by water and sometimes, eventually, by deposits.

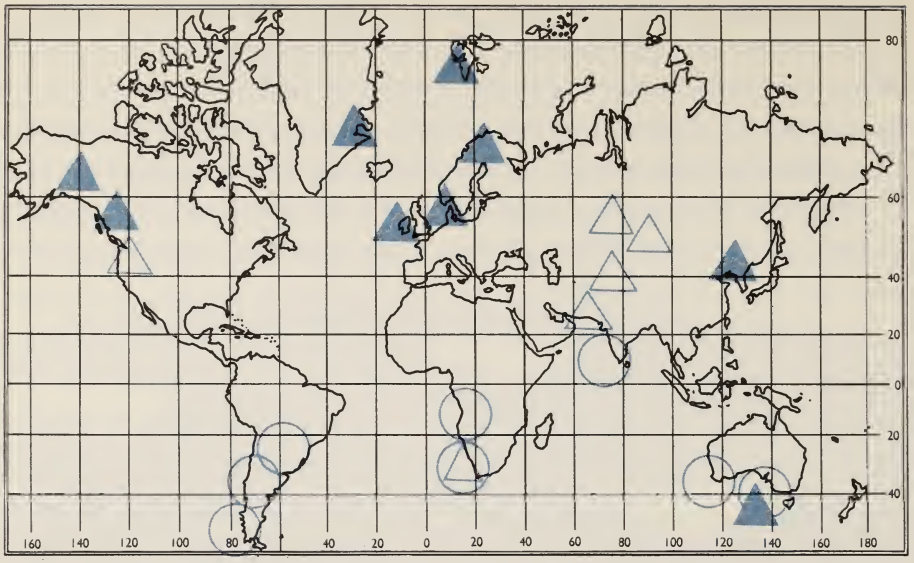
Another effect of the changes in sea level can be seen in the warmest parts of the oceans, where corals grow abundantly. At one time it was hard to account for the occurrence of so many ATOLLS – the almost circular coral reefs which crop up as isolated islands in the great oceans – but nowadays it is thought that when the sea level was lowered the cooler climate killed off the corals, with the result that many existing islands, robbed of their protective fringe of living corals, were cut down gradually to the lower sea level by ocean waves. Then, as the climate warmed up again, the level of the sea rose and corals began to grow again, building up new reefs round the edges of the islands where there was plenty of food available in the water.

*Earlier ice ages*

Of earlier ice ages perhaps the best known belong to a period about 250 million years ago, the results of which are found in the continents of South America, South Africa, India and Australia. The difficulty here is that we have evidence of ice in the Southern Hemisphere without any trace of ice in the Northern Hemisphere. Indeed, at this time, when glaciers were spreading over the ancient

Crescent-shaped sand dunes as shown above are known as barchans, typical of a desert area where, for the most part, rock is exposed and the limited amount of sand is piled up in dunes by the prevailing wind from right to left. The sand is blown up the gentle slope and tumbles down the steep side. The stronger the wind is the more elongated the dunes become.

continent of Gondwana, coal forests were flourishing in America, Europe and the Arctic regions without a sign of cold conditions. It is almost impossible to account for this by the present arrangement of continents in relation to the present poles and equator. An attempt has been made to overcome the difficulty by imagining that the whole earth's surface was moved in relation to the position of the poles so that the South Pole would move much nearer the center of glaciation (possibly at one time somewhere in South Africa) and the North Pole would lie in the Pacific Ocean, while North America, Europe, and the Arctic regions were nearer the equator. Much of the evidence of this period shows such a climatic pattern, with hotter and possibly more equatorial climates further northwards, and glaciation to the south. In the imaginary maps which have been




Approximate positions of some ancient tillites which give evidence of glaciation. The solid triangles represent a glacial horizon just beneath the Cambrian (say 600 million years or more ago). The open triangles are of uncertain age but could be the same. The circles indicate evidence of Carboniferous and Permian ice action (say 250–300 million years ago). According to Wegener's theory of continental drift the circles were once much closer together and nearer the south pole. The triangles are more difficult to explain except as a very widespread ice age.

drawn to reconstruct these conditions, a large number of places which are known to have been glaciated near that time are fitted together near the position of the South Pole, and the equator then passes through North America, Europe, and the Arctic. This then satisfied the conditions for the South Pole during that ice age and for many places where we know that the climate was warmer.

A still earlier ice age must have taken place just over 600 million years ago, according to evidence found in localities ranging from North America through Greenland, Spitsbergen, Scandinavia and

A paleogeographic map after Charles Schuchert, of the distribution of land and sea in Middle Canadian times (Lower Ordovician – about 480 million years ago). The blue areas represent the position of sea at that time where land now is. The evidence includes rocks of that age, the larger outcrops of which are shown as solid black and borehole evidence as black dots. The dashed shorelines are very uncertain. The seas would be wider in the Appalachians and Western Cordillera regions which have since been much compressed.

80°
80°
60°
60°
40°
40°
20°
20°
120°
00°
80°

China, and in the Southern Hemisphere, particularly Australia. Unfortunately the same rearrangement of the continents will not do for this earlier ice age. It may be that some rearrangement or, possibly, a slightly different pole position, may help to explain this glaciation, but the fact that the evidence is so widespread suggests that this ice age may have been more extensive than either of the two better-known later ones. Exploring even further back in geological time, we find evidence of still more ice ages, but these cannot be dated accurately and so we cannot yet build up a picture of world climate at any earlier date.

*The normal world climate*

There is, then, definite evidence of five glacial periods and possibly several more, but between these periods there is but little evidence of ice on the surface of the earth. As far as we can tell, the ice ages and our own climate are exceptional and the warmer climates in between are more typical. The climate which has prevailed over the earth for most of the last two or three billion years may well have been not only warmer than it is today, but possibly more nearly the same all over the world. It would have been warmer at the equator than at the poles, but the difference would not be as great as it is today – particularly if the proportion of sea was greater than it is now, and if there were fewer high mountain chains. Large areas of water make the climate more uniform and equable. Over long periods the sea might slowly advance on the land, owing to the higher land masses being continually worn away and their débris carried into the sea, causing the oceans to overflow the edges of the continents. Earth movements, if they were strong enough, would interfere with this process and lower the sea level, but for long periods they might have been too weak to do so.

*Climatic clues*

Within some continental areas, and particularly in places protected from sea winds by newly uplifted mountains, we sometimes find evidence of former desert conditions. Gypsum and salt deposits, left behind after the evaporation of sea water from small enclosed basins,

indicate hot, dry climates. We often find sandstones in which the sand grains are quite rounded and polished and all very much of the same size. They are known as MILLET-SEED SANDS, and are formed by the rubbing, rolling and bouncing of sand particles blown by the wind. They are often found in the form of ancient desert sand dunes hardened into sandstone. Wind-driven sand skidding over the desert polishes any rock in its path. Pebbles shaped by sand blast in this way are known as VENTIFACTS. They usually have one or more sharp edges, and a very fine smooth surface known as DESERT VARNISH. Pools of water, too, may form and dry up from time to time, leaving wet mud which rapidly dries and cracks. Should this mud be covered by blown sand, the MUD-CRACKS may be preserved, and give us a useful clue under the conditions under which the rock was formed.

In the above examples the study of rocks shows something of the climatic conditions under which they were deposited. Much may also be learned from the study of fossils. When fossils are not too old, the animals and plants may be so similar to those existing today that we can easily guess what the climate was like when they were alive. However, fossils from older rocks may be so different from present-day living things that it is harder to deduce the climate in which they lived. In studying the climate on land, plants are more useful than animals since they evolved more slowly, and they must grow in the same place over a long period. A coal deposit obviously indicates the presence of a persistent forest at some time in the past. The climate must have been warm enough for trees to grow, but not too warm, for sometimes in hot tropical climates the organic material falling from trees decomposes rapidly and disappears. It is in temperate and cool climates that peat is usually preserved. In tropical latitudes, where the difference between summer and winter is hardly noticeable, trees grow without annual rings, but elsewhere the differences between the seasons may cause a slowing-up of growth during the winter, and so encourage the formation of annual rings. The presence or absence of tree rings, then, gives some indication of the latitude, as well as of the climate in which the trees lived.

Fossil animals may also be useful in studying past climates. Very

The three ventifacts above are pebbles shaped by the sand blast of a desert wind. Smooth ridges separate the polished faces, each of which is due to a prevailing wind. Rocks with slight differences of hardness may have their inner structure displayed; the lack of this in these specimens shows them to be of uniform rock like quartzite.

often these fossils are formed in the sea, and the information we can get from them concerns the temperature of the water, which may be rather different from that of the air above. Coral reefs grow only in warm waters, and many other fossils with limy skeletons are also dependent upon warm seas for their life and growth. Indeed, limestones of all kinds suggest warm, rather than cold, conditions for their formation.

From such clues and many more we have the impression that world climate has, on the whole, been warmer and more uniform in the past than it is today, and that we are at present in an exceptional time belonging to one of the ice ages. It also seems that climate is affected very much by the proportion of land to sea, and this also seems to have varied at one time and another. But changes in climate cannot be explained entirely by changes in the proportion of land to water. Another, perhaps obvious, factor is the sun's radiation. Climate depends very largely on the strength of the sun's rays in different parts of the world at the same time. However, this may not account for some major climatic changes and it is simpler to explain some of these past climatic changes by assuming that the brightness of the sun has changed slightly from time to time. Changes in the sun's radiation, then, together with changes in the distribution of land and sea, and major crustal movements may account for all the plast climatic history of the earth. When we know more about the climatic history of the earth we may discover something of the sun's own past.

# 11. The story of life

One of the earliest and most exciting events in geology was the realization that fossils were the relics of ancient living things. It was then noticed that older rocks contained fossils different from those found in newer rocks, and that collections of fossils made from successively younger rocks gave a picture of the different and changing inhabitants of our globe. The story of life has been pieced together through the identification and comparison of many millions of fossils collected from different parts of the earth's crust. In spite of this seeming wealth of material, only the most minute part of the whole procession of life is represented. When they die most living things are eaten, or decay, without leaving any trace, so that very few are ever preserved at all. Many of the rocks which do contain fossils are eroded or metamorphosed, and of those that escape destruction only a few may be accessible to geologists, who normally have to rely upon scattered localities in quarries and along cliffs. It is really remarkable that from such widely dispersed relics of former ages any idea of the story of life can be worked out at all.

The oldest of these rich collections of fossils comes out of rocks from the Cambrian era, which began about 600 million years ago Rocks older than these are known as PRECAMBRIAN, and may be from three to five times as old as the Cambrian, or even older. Among the very oldest rocks are limestones which seem to have been formed in warm seas, and there are structures in some of these limestones apparently caused by the activity of minute plants or ALGAE. So for at least 2,000 million years preceding Cambrian time, almost the only fossil records we have are traces of lowly forms of plant life, probably inhabiting warm seas. Only towards the end of this long period do we find indications of other forms of life. Many of these clues are rather uncertain, since they are often no more than trails or

tracks, presumably made by small creatures living on the sea floor.

Yet when we come to the beginning of the Cambrian period (about 600 million years ago) fossil records from many parts of the world show that there were already in existence various quite advanced forms of marine life. Although the animals were all different from those living today, they were clearly related to them, and indeed a great many of the groups of animals we know today seem to have been represented in those early times. How was it, then, that this burst of life made its appearance throughout the world so suddenly, and yet in so advanced a stage of development?

Various suggestions have been made. Some have thought that a great change, perhaps a chemical one, took place in the seas at the time, and that creatures living there without shells or skeletons were suddenly able to make hard parts, which were then preserved as fossils. There is, however, no evidence to support this view.

Another possible answer is that the development of animal life may have been exceedingly rapid at first, the early stages being confined to seas whose deposits have not yet been discovered, and that at the beginning of Cambrian times there was possibly a sudden spread from the centers of creation to wider areas. In many parts of the world, just beneath the oldest Cambrian fossils, there is in fact evidence of perhaps the greatest ice age we know about. It is likely that in late Precambrian times the world climate was much cooler, and that great ice caps existed. The seas would then be lower because of the amount of water stored as ice on the land. These conditions would restrict living things to the warmest seas, which might have been isolated from each other because of the lowered sea level. Towards the end of this ice age there would have been a slow warming up of the whole earth's surface; the ice would have melted and raised the sea level. When this happened, the hardy animals which had been confined for so long to a few equatorial sea basins would have had a chance of spreading throughout the seas as these became warmer and encroached on the land. This may possibly account for the apparently simultaneous appearance of Lower Cambrian FAUNAS in many parts of the world. The layers of fossil-bearing Cambrian

rocks which rest on a great series of apparently unfossiliferous Precambrian rocks show that something of this sort must have happened.

It is a fascinating problem, and one that cannot be solved easily. We are quite ignorant about the process of creation – the beginning of life in remote Precambrian time, and the life just before the sudden appearance in Cambrian seas of myriads of beautiful marine animals. From Cambrian times onwards to the present day the animals, and later the plants, show immense variety of form, and each succeeding age has its own particular kinds.

The many geological ages, each distinguished by its own set of fossils, have been grouped together into three main eras – the Era of Ancient Life, or PALEOZOIC; of Middle Life, or MESOZOIC; and of Recent Life, or CENOZOIC. In each case the suffix "zoic" comes from *zoos*, meaning life, and the prefixes *paleo*, *meso*, and *ceno* (*kaino*) are used in many other connections, especially *paleo*, which means ancient. These names were first suggested before any evidence of life had been found in Precambrian rocks, and so the three terms were thought to span the whole range of life on earth. It is now clear, however, that the Paleozoic was preceded by still more ancient life, and the use of terms such as PROTEROZOIC and EOZOIC has been suggested, but these cannot mean much until we know more about the nature of the earliest life. At any rate the life of Paleozoic, Mesozoic and Cenozoic times is comparatively well known. Paleozoic time covers a very large span, from about 600 to about 225 million years ago, and can be divided into Lower, or older Paleozoic, and Upper, or younger Paleozoic.

*Lower Paleozoic*

In Lower Paleozoic times life existed almost entirely in the sea. There may have been life on land or in fresh water but what evidence we have is doubtful. The marine life known from fossils is mostly animal – though from what we know about animal life there must have been abundant plants (perhaps of a simple type) for the animals to eat.

Some of the animals of the Lower Paleozoic were not unlike those living today. There is evidence of worms and jelly-fish, which are not

easily preserved because they lack skeletons but which occasionally left tracks or impressions in fine-grained mud that make it clear they were not very different from those of the present day. A number of MOLLUSKS, or shellfish, including snails and bivalves (two-valved shellfish, like mussels and oysters) as well as creatures distantly related to the present-day NAUTILUS, were living in the seas of those days, but they were not as important as they are today. The shellfish which were common in those days are not common now. They were the BRACHIOPODS, or lamp shells, which, like the mussels and oysters, are also bivalved shellfish but have their valves at back and front instead of to left and right. The soft parts between the shells are also very different from those of the mollusks.

CORALS are well represented in Lower Paleozoic rocks. While some of the coral colonies may have been many feet across, they were very much smaller and in many ways different from present-day coral reefs.

Some of the other animals which were common in those days are now extinct – for example, the interesting group known as GRAPTOLITES. These were small thin strands, or living filaments, made up of a series of minute individuals strung together. When they are found as fossils they appear on the surface of black shales as a series of thin lines arranged in different patterns, rather like pencil lines on the rock. ("Graptolite" comes from the Greek *graptos*, meaning "painted or marked with letters".) For some time they were thought to be related to corals and sea anemones, but they are now considered to have been more like some of the very primitive VERTEBRATES. They are believed to have lived floating near the surface of the sea, attached to floating seaweeds or even producing their own floats. In this way they spread very widely under the surface of the seas, some of which were too deep or too stagnant to support life on the sea floor. On dying they sank to the bottom and were preserved in deposits, some of which have no other fossils. Being independent of sea floor conditions they spread widely and so have become very important as INDEX, or ZONE FOSSILS. From them we can tell whether rocks formed in different places are of the same age, according to whether or not they

Graptolites fossilised in shale. Graptolites lived between about 4 and 500 million years ago. Because they evolved so rapidly and spread widely in the surface layers of the sea they are admirable zone fossils. The species of *Didymograptus* illustrated fixes the age of the rock to one of half-a-dozen zones in the Lower Ordovician.

contain the same graptolites. During the middle part of the Lower Paleozoic, twenty or more zones with different graptolites can be distinguished because of their rapid development and ease of recognition, nevertheless they do not seem to have survived into the Upper Paleozoic.

The TRILOBITES, so-called because of their three lobes, belong to another extinct group which lived in Paleozoic times. They were particularly important in the lowermost Lower Paleozoic. A fossil trilobite looked rather like a fairly large woodlouse, and it lived by crawling or swimming over the bottom of the sea, where it probably fed on dead organisms. Each trilobite had many segments, each with a pair of legs attached beneath, and, like the woodlouse or the modern crab, had a horny skin on the outside – a characteristic shared by all the ARTHROPODS (animals with jointed legs), including crustaceans, insects and spiders. The trilobites were some of the earliest marine arthropods, and their fossils, which are found only in Paleozoic rocks, are mong the most important of the Cambrian fossils.

Towards the end of the Lower Paleozoic another group of animals – the MEROSTOMES, possibly related to the trilobites – became very important and grew to enormous size. Their nearest representatives today are the scorpions and king crabs, but some of the best known

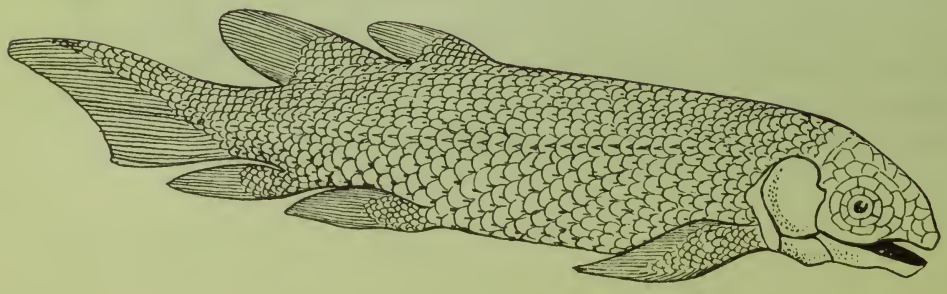
of the extinct types are the fossil EURYPTERIDS, which grew to six or 10 feet in length, and were rather like giant flat lobsters.

Various other groups were also represented during Paleozoic times, such as the SPONGES, which have continued throughout geological time, playing a small but significant part in the life of successive ages. Likewise a still more simple group, the PROTOZOANS, or single-celled animals, may have been among the first of the animals, but because of their small size and simple skeletons they are not easy to identify in the older rocks. The ECHINODERMS (spine-covered creatures), too, are represented in the Cambrian, and they include the sea urchins, starfish, and sea lilies, as we shall see later.

*Upper Paleozoic*

Several new developments distinguish the Upper from the Lower Paleozoic. In particular, in this era we have evidence of vegetation on land. During Upper Paleozoic times, after primitive land plants had established themselves the scene changed. They were succeeded by mighty coal forests, whose great trees looked like tropical palms or giant ferns but were, in fact, very different. The greatest coal deposits belong to this era. We have evidence, too, that at the beginning of Upper Paleozoic times there was a rapid spread and growth in size of fish. The best known of these apparently lived in freshwater lakes and seas. They are well known from the Old Red Sandstones of Europe, in which some of the armored fish made fine fossils showing their highly decorative protective covering.

*Dipterus*, a genus of Devonian lung fish (350–400 million years ago), was not only an important member of the rich fish faunas of Devonian times but may well have been an ancestor of the land vertebrates. Lungs may have been useful to fish in freshwater ponds liable to dry up.



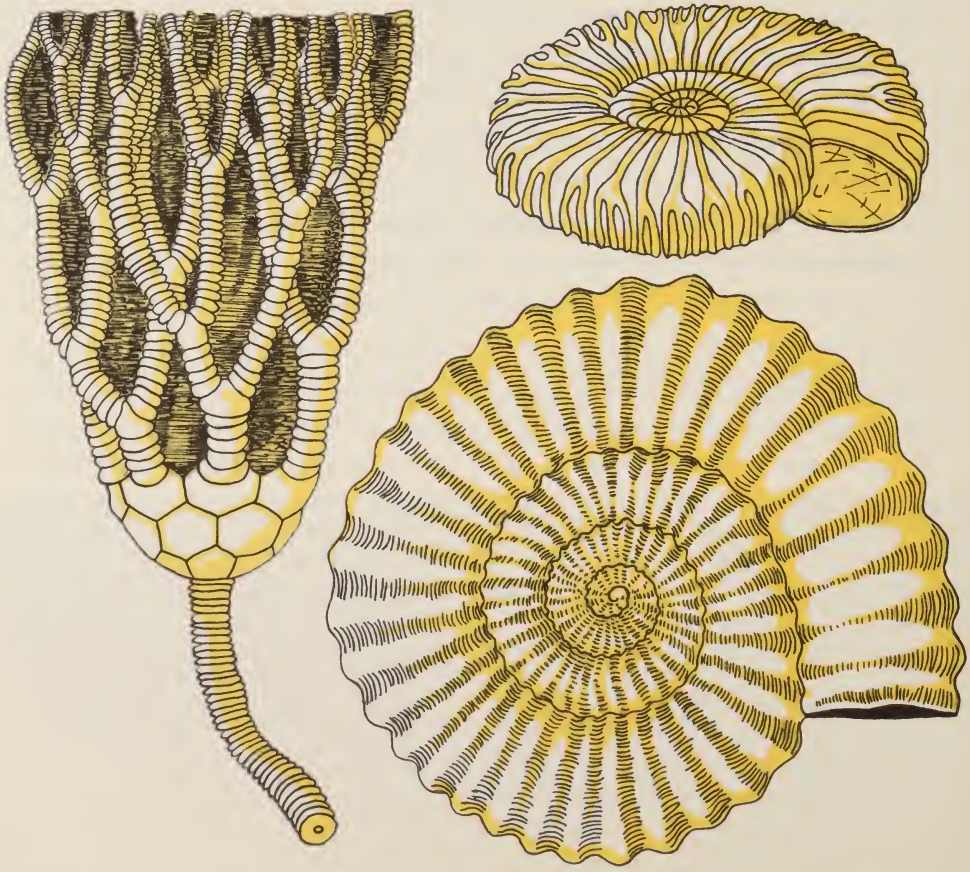
Since some of these early fish show signs of developing lungs and of being able to survive a dry summer when the lake in which they were living was reduced to a muddy swamp, it is thought that the earliest land animals may have emerged from the water in this way. The various fish include the undoubted main stock of the vertebrate, or backboned animals. It looks as though some of the Upper Paleozoic fish developed the capacity to crawl out on to dry land, for the earliest AMPHIBIANS – a group of vertebrates including frogs and newts – are associated with some of the fine coal forests, and a little later some of the earliest REPTILES, related to present-day snakes and crocodiles, appeared. In Upper Paleozoic time neither the amphibians nor the reptiles played any great part in the life on land, but they are nevertheless of great interest because of their early appearance and the possiblity that they represent some of the forerunners of man on earth. Insects appear to have become widespread at this time, and we can imagine that among these ancient coal forests there were four-legged beasts crawling in the mud and insects flying in the air, while fish were swimming in the lagoons.

Life in the sea was not so very different from that of the Lower Paleozoic. Graptolites had disappeared, trilobites were rare, and eurypterids had ceased to be important. Corals and brachiopods played a still larger part in the life of the Upper Paleozoic seas. Mollusks, too, continued to inhabit the seas in large numbers, but some of them apparently moved into fresh water, and even on to the land – for instance, in the Coal Measures, between coal seams, bivalve shells are found which are very much like freshwater mussels. At sea, the mollusks of one particular group, known as the GONIATITES, related to the present day nautilus, became very important during this period. Their coiled shells were subdivided into a series of chambers, of which the animal occupied only the last, or outer chamber. As it grew the animal would secrete more shell around itself, and then lift itself up from the last partition, or SEPTUM, and build a new one, leaving an empty CHAMBER behind it. In this way a shell was formed into which gas could be secreted and which was thus capable of floating. So here again we have marine animals which, like the graptolites, floated on

the surface of the sea and were therefore likely to be found preserved in deposits all over the earth, regardless of sea bottom conditions. The goniatites, then, represent another series of zone fossils, useful both because of their wide distribution, and because each successive age was characterized by different and distinctive kinds.

In the later part of the Upper Paleozoic some of the single-celled animals reached quite a large size and produced skeletons nearly a quarter of an inch long, containing many chambers in complex forms. These FUSULINES are rather like grains of wheat in size and shape, and sometimes whole deposits of limestone are formed from them. Limestones may also consist largely of the separate cylindrical plates from the stems and tentacles of sea lilies, or CRINOIDS, which belong

The coiled ammonites on the right are examples of a group which was very important in Mesozoic times; and during the Jurassic Period, particularly, enable very precise subdivision and correlation by zoning. The crinoids, or sea-lilies, shown on the left, were especially common in Carboniferous times. Their skeletons usually break into separate discs.



to the echinoderm group. This group also includes the SEA URCHINS, which appear for the first time in the Upper Paleozoic.

*Mesozoic*

The Mesozoic fossils differ in many ways from those of the Paleozoic. In many parts of the world it is hard to find evidence of life during the transition, for at that time there seem to have been widespread earth movements, and conditions for many living things may have been difficult. Many of the main groups of Paleozoic fossils do not appear to be represented in the Mesozoic. Some groups did, however, carry on to assume great importance in the new Mesozoic lands and seas.

In the seas, perhaps the most important development during Mesozoic time was the great increase in variety and numbers of the AMMONITES – coiled mollusk shells with successive chambers, belonging to the same group as the goniatites. Just as graptolites and goniatites are used for zoning Paleozoic rocks, so the ammonites are the chief zone fossils of the Mesozoic. They are often by far the most useful indicators of the exact age of these rocks, since they are so varied and each kind was very widespread for a short time.

Other mollusks also increased in importance during Mesozoic time, particularly the PELECYPODS, which were bivalves related to present-day mussels and oysters. Corals and brachiopods continued to thrive in limestone-forming seas. Although sea lilies decreased in number, sea-urchins became abundant and are useful and variable fossils, ranging from the thin-shelled burrowing heart urchins to the large round stronger-shelled urchins protected by many spines.

But perhaps Mesozoic life is best known for its many strange reptiles. The size of some of these extinct monsters far exceeded that of any land animals living today, and their formidable appearance gives the impression that they were superior in strength to all present-day creatures except the whale. The variety of forms these reptiles adopted is truly wonderful. Some took to the seas and developed strong swimming paddles, like the short-necked ICHTHYOSAUR and the long-necked PLESIOSAUR. Others probably lived in shallow water or in

swampy places where the great weight of their bodies was partially supported, but they still walked on the bottom, with their long necks reaching out of the water or feeding on vegetation under the surface. Such were the DIPLODOCUS and the BRONTOSAUR, which were among the largest of all, and far exceeded the largest elephant in size.

Some of the DINOSAURS which adapted themselves to life on dry land apparently developed great speed, usually by means of two powerful back legs and a large supporting tail, and their huge teeth show that they depended on lesser reptiles for their food. The IGUANODON and the TYRANNOSAUR are examples of this kind of beast. Others on land, such as the STEGOSAUR and the DIMETRODON, developed enormous plates and spines, no doubt to protect themselves against preying monsters.

It seems that the very first birds may have developed from fast-running, climbing, or flying reptiles like the PTERODACTYL, for large but primitive birds such as the ARCHAEOPTERYX have been found in Mesozoic rocks. Many of these land reptiles and birds lived in forests rather different from the Paleozoic coal forests. Towards the end of the Mesozoic Era the forests were similar to those of today, but the earlier ones of that era represented an intermediate kind of plant life,

*Ichthyosaurus*, a genus of aquatic reptile common in Jurassic times, say 150 million years ago. The reptiles are typically equipped for life on land but some groups of reptiles became highly adapted to marine life (as some mammals did later, e.g. the dolphin and whale).

Reconstruction of *Archæopteryx*. A fossil found in a Jurassic limestone in Germany has a reptile-like skeleton but impressions of feathers are preserved. This is one of the earliest known birds, which must have evolved from a group of reptiles. This freak discovery underlines the difficulty of getting a complete story of life.

of which the MAIDENHAIR TREE, or GINKGO, is one of the very few living survivors.

*Cenozoic*

Another great difference distinguishes Mesozoic and Cenozoic fossils. In the seas the ammonites died out altogether and another group of mollusks became more important – namely the GASTEROPODS, or snails, which lived not only in the sea but also in freshwater and on land. The pelecypods, or bivalves, also continued to multiply in large numbers, whereas the brachiopods were limited to fewer kinds. Other important marine animals were, as before, the protozoans – the

single-celled animals. Only those which secrete limy or siliceous skeletons are known geologically – the lime ones being known as FORAMINIFERA, or forams. Most of these, such as GLOBIGERINA, are very small, and can only be seen clearly with the microscope. However, from time to time members of this group have achieved quite considerable size; the fusulines from the end of the Paleozoic era, and some Cenozoic forams are good examples. In the Lower Cenozoic rocks the button-shaped NUMMULITES are found throughout the Old World, and those from Gizeh in Egypt and from the Paris Basin are famous. In the Pacific area other large forams such as LEPIDOCYCLINA and MIOGYPSINA are common, some of them being more than an inch in length. They are usually very abundant, so that each chip of rock may contain several individuals. Other common marine fossils found in Cenozoic rocks include sea-urchins as well as many fish, especially the sharks which we recognize from their resistant fossilized teeth. Of the marine fossils the forams provide the best means of CORRELATION in the Cenozoic Era.

On land during Cenozoic times the contrast with the Mesozoic scene is very striking, for in place of the large reptiles, which disappeared at the end of the Mesozoic Era, the Cenozoic lands were inhabited by MAMMALS. So just as the Mesozoic Era is known as the age of reptiles, the Cenozoic Era is the age of mammals. The plants on which these mammals fed were very similar to those now living, perhaps changing gradually from the warm and wet forests of the early Cenozoic to cooler and sometimes more widespread grasslands towards the end of Cenozoic times.

The name Cenozoic itself indicates that the life during this era was recent in appearance. Before the name was used Lyell proposed to divide the rocks of this era according to the proportion of recent and living forms found in them. The result is that we have today the well-known terms EOCENE (dawn of recent), OLIGOCENE (a little recent),

*Pteranodon* is a genus of remarkable flying reptiles with a wing span of up to 25 feet, in Upper Cretaceous times. Reptiles were then able to compete successfully in the air with birds, known already to have developed at least 50 million years earlier, but they became extinct before the end of the Cretaceous Period.

Miocene (minor part recent), Pliocene (major part recent) and Pleistocene (most recent) as divisions of the Cenozoic Era. These terms were first proposed in Europe from the study of pelecypods and gasteropods, but they may be applied throughout the world. It is remarkable that, even before any idea of evolution had been accepted, the principle that the succession of life throughout the ages tended to show an increasing similarity with present-day life was well established. This principle was particularly easy to apply to the Cenozoic rocks, in which many of the fossil shells are almost identical with those of creatures living today.

*Evolution*

The general story of life outlined above was known in some detail by 1820, and very much more thoroughly by 1850, by which time long lists of fossils were known from many different rocks whose order in the succession was well established. It was not until 1858, however, that Darwin and Alfred R. Wallace together put forward their idea of the way in which the changes had taken place. This was not the first time the concept of evolution had been considered, for ever since the beginning of the century the succession of life was thought to reveal a natural or miraculous progression of forms, generally from the simple to the complex.

However, no one had really found enough evidence to argue that the successive inhabitants of the world were related in a continuous series of families in the way that we may trace back our own history through parents, grandparents and so on. To those who today accept the idea of evolution it is almost inconceivable that there could be any other explanation, and yet it is not easy to show from fossils that a slow and almost imperceptible progression of life has taken place. The fossil record, as we saw at the beginning of this chapter, is so incomplete, and there are so many gaps between the different formations of rocks, that it was not unreasonable for the samples shown in geological museums to be regarded as successive creations. To the modern scientist the idea of successive creations may somehow seem more miraculous than the idea of evolution. But each idea is, in its

own way, rather wonderful, and considering the evidence which was available in 1850 it is not surprising that many were reluctant to accept the essential idea of continuous threads of life stretching from the beginning to the present day.

Darwin assembled a great mass of evidence, both from a study of fossils – including some Cenozoic mammals found in South America – and from his study of the breeding of domestic animals. In his *Origin of Species* he put forward the most powerful arguments for supposing that evolution had taken place by a process of natural selection. He had noticed that various kinds of dog, horse, or pigeon could be bred by artificial selection – that is to say, by always breeding from the animals which most nearly resembled what was wanted. Children of any parents vary very much, and it is always possible that the differences between them may help some, rather than others, in different circumstances. The idea of natural selection was that throughout the enormous span of geological time, if there was any advantage in a slight difference which some members of a family had over other members, they would tend to survive in difficult circumstances, and their offspring would inherit this advantage. Although perhaps ten or twenty generations might show no noticeable change, many hundreds, thousands, or even millions of generations would allow this process to work, slowly changing the whole stock. Darwin realized that we could not expect to illustrate this gradual process from fossils alone because of the very small chance of finding more than a few isolated examples, and he was the first to point out how incomplete the geological record must be.

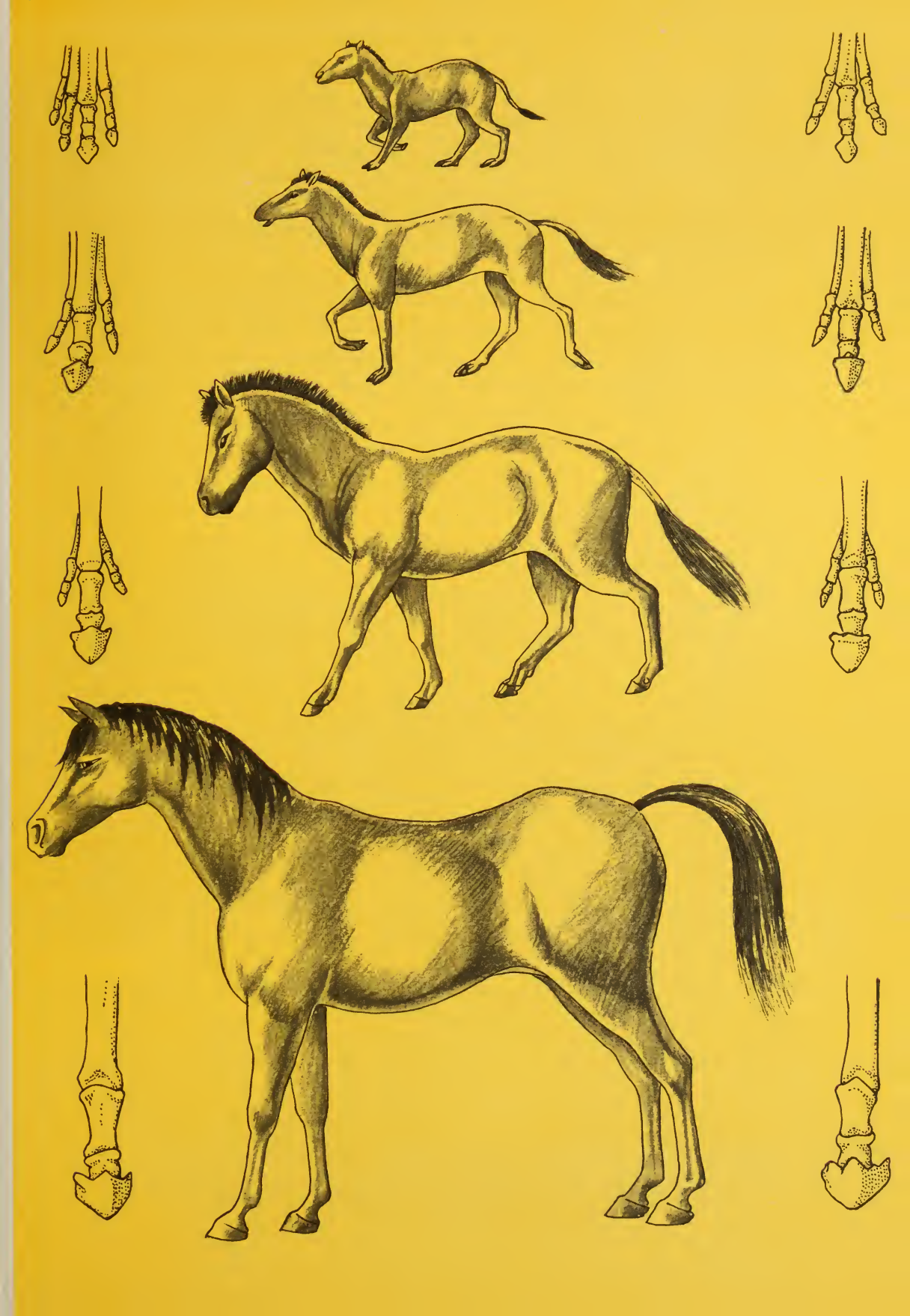
Indeed, the most powerful argument for evolution by natural selection does not come from the study of fossils at all, for it is virtually impossible to demonstrate such a complex process unless one can show some definite family relationship and be quite sure that one fossil represents the true ancestor of another. The evidence for natural selection comes strongly enough from the study of living things, where it can be observed how the fittest do survive. Geologically we can only assume that the fittest have survived, and guess at what their advantages might have been over other types. It is easy,

for instance, to understand that some of the great reptiles of the Mesozoic Era would gain an advantage by growing larger and larger, some by developing bigger and more powerful teeth and jaws to eat their neighbors, and that, as a result, others would develop thick, heavy armor and avoid being eaten; similarly with the capacity to run or to swim faster. They all developed their special skills.

But ultimately all the saurian reptiles seem to have died out. Many reasons have been suggested for this – for instance, that they became so highly adapted to their own particular environment that they were simply not able to survive any sudden change which deprived them of their normal way of life and food. Another suggestion is that the smaller mammals developed as more efficient competitors. The mammals certainly had a larger brain capacity, and with their warm blood were more active, even though they were considerably smaller. Being creatures of greater intelligence they may have had the first pick of available food and so deprived the more ungainly reptiles.

Whatever the cause, the mammals thrived and developed along many different lines. Some of the most primitive of them, like the duck-billed platypus, are only known living where they now survive in Australasia. In Eocene times there was a tremendous development of the so-called archaic mammals, such as UINTATHERIUM and CORYPHODON, which became specialized in various ways. Other archaic mammals included representatives of CARNIVOROUS (flesh-eating) and HERBIVOROUS (plant-eating) types similar to the modern mammals. Many of these families died out towards the end of the Eocene and Oligocene Periods, apparently in competition with some of their better adapted relations, for the archaic mammals still had a small brain and poorly-developed teeth compared with the modern mammals. Here again the penalty for over-specialization may have been that they became too unadaptable to compete with others of

From the small *Eohippus*, illustrated at the top, in Eocene times, the modern horse developed, and many extinct species are known both on the main evolutionary line between them and on branches which did not survive. The main structures used to identify fossils are the feet (which became more simple) and the teeth (which became more complex).



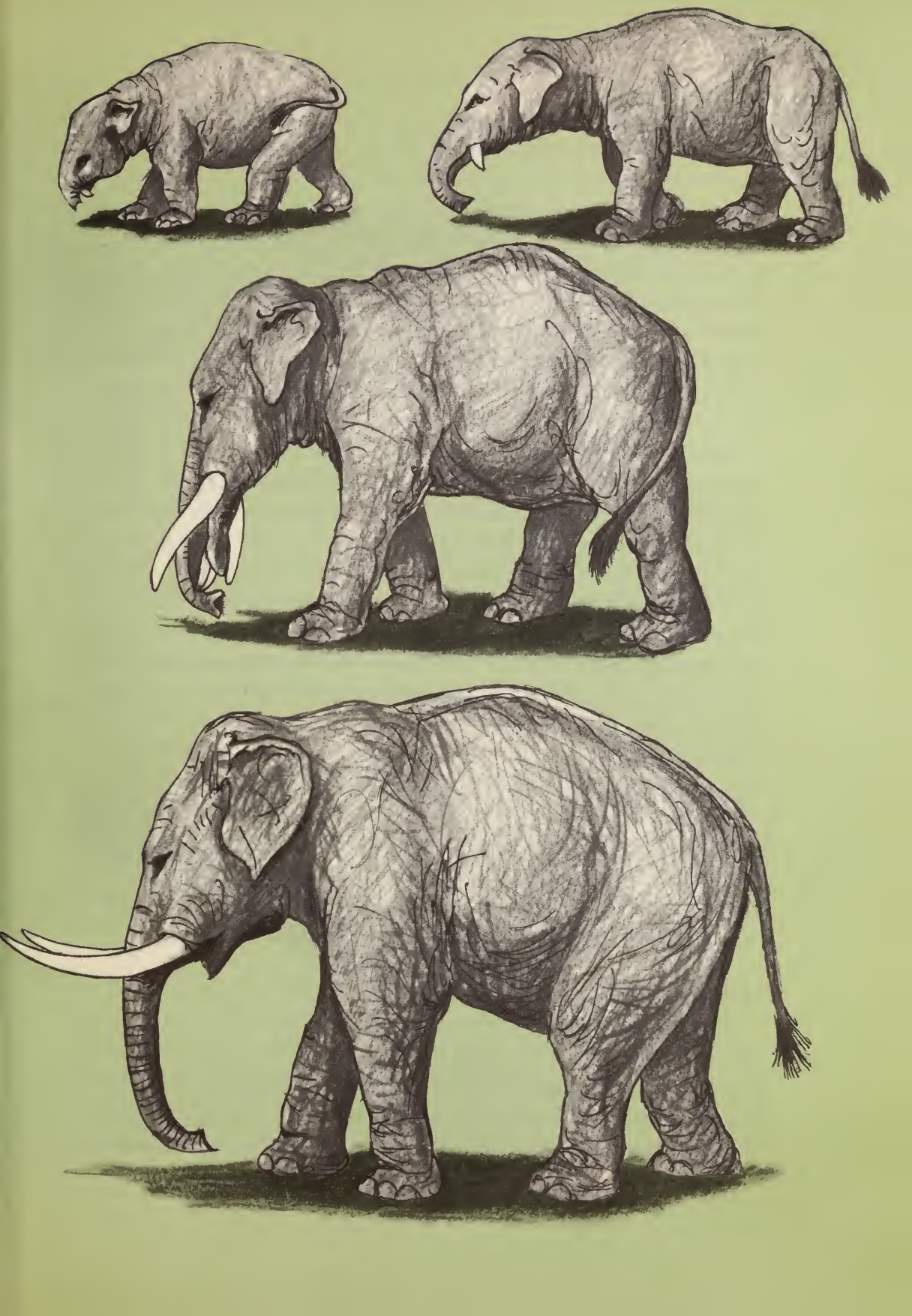
better mental and dental equipment, and so the archaic mammals were ousted and a great variety of modern mammal stocks multiplied in their place.

There are many stories of evolution within these modern mammal families – for instance, the story of the horse, well known from a great selection of fossils found in North America. This shows a steady growth in size and the specialization of teeth for grinding. By this means, apparently, the horse adapted itself to living on the grasslands which were increasing in that area throughout the Cenozoic Era. It depended on speed for its safety, and its limbs show a slow reduction from five-toed feet down to a single main toe. Sufficient fossils of these successive stages of development have been found to establish the series firmly. The evolution of many other animals has also been worked out from fossils, including the development of the camel, the growth in size and specialization of the elephant with its massive grinding teeth and peculiar tusks, and the adaptation of warm-blooded four-footed mammals to the sea, such as seals and whales.

It has been argued that the success of man himself may be due to his having avoided specializing in any physical way which might have limited him to a particular environment, and instead having developed his mental capacity and thus gained the advantage of any new situation. Man thus achieved adaptability in living, which led ultimately to civilization and an interest in his own past history.

Fossils give us glimpses of the story of life, but our knowledge is very incomplete, and part of the excitement in fossil-hunting is the chance of filling yet one more gap. Without fossils we could only guess at the way in which evolution has taken place. With their help we can actually see fragments of the story of life itself.

The Elephants are a group first known from Egypt, e.g. top left: *Moerotherium* (Upper Eocene), top right: *Palaeomastodon* (Lower Oligocene). Later elephants were widespread, e.g. centre: *Gomphotherium* (four tusks: Miocene). Of many Pliocene genera only two survive today, e.g. lower: *Elephas* (the Indian Elephant).



# 12. The time-scale

What do we mean by the age of a rock, and how can it be known? We can fit events into a story, finding, for instance, that the age of mammals followed the age of reptiles, or that this glaciation followed that mountain-building. This can be done without any absolute knowledge of time. But if we could know the date, in years, of different events, it would give both the order and the time scale. The problems of relating diverse things into a connected story are common to both geology and history, and in each case dates give a useful framework.

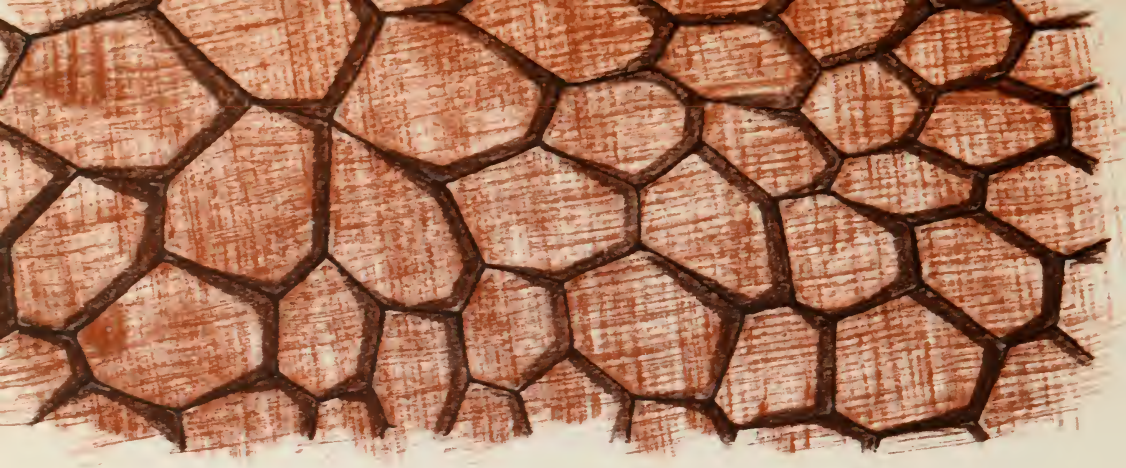
Although many estimates have been made in the past, it is only during the last twenty or thirty years of this century that any real idea of the age of some of the older rocks has been worked out. Before this, men could merely guess, and their guesses ranged from many hundreds and thousands of millions of years to perhaps only a few million years, the latter being the more popular view. For most purposes, however, as long as we can tell in which order rocks were formed, and which rocks in different places are of the same age, it does not matter much how many years ago it all happened. A film or a play compresses the action of some years, months, or days into a few hours or minutes, and providing the essential events are put in order the meaning of the story does not alter, except that a great deal of detail is missing. The same applies to geological reconstructions, which at best only provide small fragments of the whole story.

*The law of superposition*

The first and fundamental principle in stratigraphy, or the study of historical geology, is the LAW OF SUPERPOSITION. This means that if rocks are laid down one on top of the other, the ones at the bottom will be the oldest, and those at the top the youngest. This obvious principle holds good as long as sedimentary rocks are laid down in the

ordinary way. However, it may be upset when, for instance, earth movements turn the rocks upside down, so we have to use various means to find out whether rocks are, in fact, the right way up or not. If, for instance, the roots of a tree have been fossilized in their growing position, embedded in the original soil, it is easy to tell at a glance whether the rock is the right way up. Worm tubes may also help in this way, but such easy clues are not at all common, and we have to fall back on less obvious structures. The ripple marks, for example, which are often to be seen on the seashore between tides, usually have sharp crests and rounded troughs, so that when they are fossilized the sharp crests will probably point upwards in the succession towards the younger rocks. Again, any small cavity in the surface of new sediments will tend to fill up with later sediment, which may eventually form a continuous layer on top of it. The filling and the upper layer may be of a different color from the lower layer, and when this is seen it will be obvious which is the older rock. Cracks of this sort are common when the older deposit was a mud which dried up on the surface, perhaps between tides or floods, and although the cracks are usually removed by the next arrival of water they are sometimes preserved and filled with later sediment.

Ripple marks preserved in a slab of sandstone indicate how the water was moving at the time of formation. They are useful also in confirming the top and bottom of the strata in which they are found, if sharp crests and rounded troughs can be distinguished.



Mud cracks are found today where water has left mud to dry and crack open. These cracks are preserved if, say, sand is deposited next and fills in the cracks. Millions of years later the cracks may stand out preserved in the more resistant sand, when the bedding plane is again exposed. They can also be used to confirm the top and bottom of the strata.

Sometimes after a great submarine disturbance clouds of water-borne dust billow up in the bottom of the sea and sink down slowly afterwards. The largest particles will fall to the bottom first, followed gradually by smaller and smaller particles, and the result will be a sediment graded from bottom to top. This is known as GRADED BEDDING, and so if a gradual change from coarse to fine is observed in a rock we know that the change must be from old to young. Sometimes a whole series of rocks may consist of repetitions of graded beds, in which there is generally a sudden break from fine to coarse, followed by a gradual change back to fine.

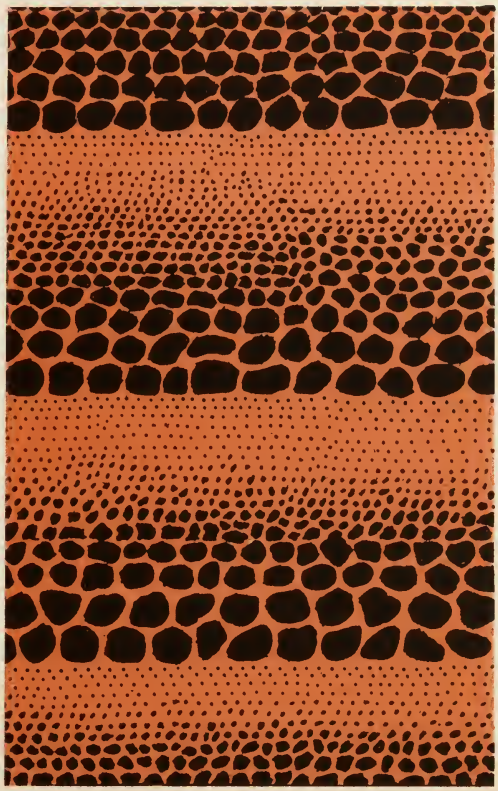
There may be cavities in fossils which at first are only partly filled up with sediment, the remainder being filled more slowly with some different-colored mineral from solution. Clearly the first sediment would be at the bottom of the cavity and the clear crystals at the top, and this would indicate the way up when the cavity was filled.

Thus in regions where rocks have been much folded, we can often tell the relative ages of different layers. But in the early days the first advances were made in areas where the rocks were not badly disturbed, and where sedimentary rocks spread out with a nearly flat structure over many miles. It was possible to trace certain conspicuous bands and find them in different quarries, cliffs and cuttings, and then, by comparing their position, to work out the order of sedimentary rocks

over a wide area. By this means the first geological maps were drawn, the conspicuous bands being marked over the countryside wherever they were found, and the different rocks in between them being distinguished on the map by different colors. The whole picture which emerged was of a series of layers, each formed at a different time, one after the other. The ordinary geological map showing sedimentary rocks is still colored in this way, so that one of the first things to find out, in mapping, is what order the rocks are in and which are the oldest and which the youngest.

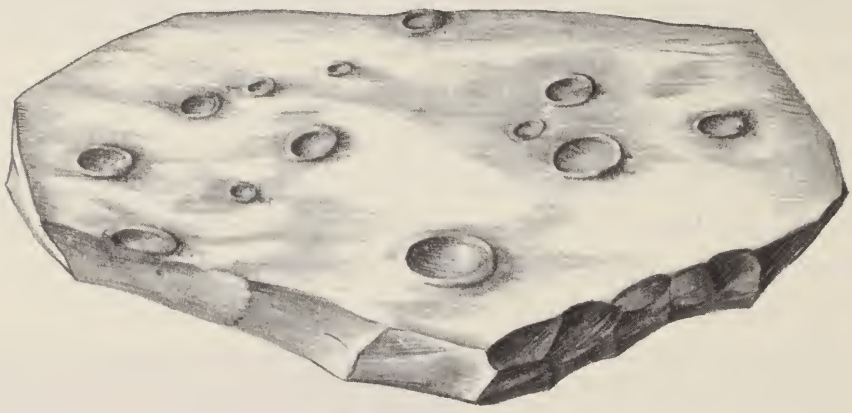
*The geological systems*

This work of mapping rocks, which is going on today all over the world, was begun in France and England at the end of the eighteenth century. It was a tremendous discovery when Cuvier and A.



A diagram showing the sedimentary sequence known as graded bedding. Each new deposit begins with coarse sediments and passes gradually upwards into fine, then suddenly coarser again. This is due to sudden arrivals of sediment-laden water, which deposits the large sediment first and then the fine. Seasonal change in glacial lakes is a common cause.

Brongniart in France and Smith in England showed that each of the distinctive formations they had been mapping had its own peculiar fossils. This opened up quite new possibilities, for, instead of depending only on finding sedimentary rocks in a particular order and then tracing some of them across the country, it became feasible to look for rocks with the same fossils, even when they were far apart,



Raindrop marks are often noticed in fine wet mud, and occasionally these impressions are preserved in a sedimentary succession. Unlike ripple marks and mud cracks, these structures are rare and not easy to interpret since small spotty concretions may give the same appearance.

disconnected, and not very much alike. In this way rocks in places separated by many miles, and even by the sea, could be compared according to their fossil content, and this proved to be a reliable method for identifying the rocks themselves. The first half of the nineteenth century saw a large number of rock formations, known locally and identified by distinctive fossils, grouped into systems.

It was enormously encouraging that these systems, with the same general kinds of fossils, were found in different parts of the world, and the early American geologists discovered rocks which, while themselves quite different from those in Europe, contained fossils sufficiently similar for them to be placed in the same systems as in Europe. This process has since been developed to a remarkable extent, and what we know as correlation – that is to say the comparing

of rocks of the same age in different parts of the world – was extended to still smaller subdivisions known as stages, which could be subdivided yet again into zones over small areas. A ZONE may be identified by a particular fossil, or association of fossils, which is not found in the rocks below or above. If a fossil is widespread, and if evolution into something quite different was rapid, it can be used in this way to identify rocks which were formed at the same time – that is, which belong to the same zone. And so sedimentary rocks from Cambrian times onwards, if they are fossiliferous, have been divided into a long succession of zones, which are grouped together into STAGES. These stages have turned out to be the most convenient units for correlation throughout the world. A number of stages together make up a system, and the earliest of the systems is the Cambrian. The Cambrian System of rocks was formed in the Cambrian Period, and the various periods are then grouped into the Paleozoic, Mesozoic, and Cenozoic eras.

It is interesting to look into the origin of the names of some of the systems. CARBONIFEROUS refers to the coal-bearing and associated rocks in Europe and America. CRETACEOUS, meaning chalky, was used because some of the first Cretaceous rocks to be described in England and France were the famous chalk rocks on either side of the English Channel. Other names such as Eocene, Oligocene, Miocene, and Pliocene, refer to the nature of the life which existed at those times. But most of the system names, and nearly all other stratigraphical names, are taken from some place where the rocks were first described. Thus the name DEVONIAN, which applies all over the world, was given to the system whose rocks were first described from Devon, in England, though in fact the system is better developed in America. Cambrian comes from an old name for North Wales, PERMIAN from a town, Perm, near the Ural Mountains in Russia, and JURASSIC from the Jura Mountains in France. The name TRIASSIC is an exception, for it means three-fold, and is so called because in Germany it was first defined as a system with three very clear groups of rocks. All these terms are now used quite generally, without much thought as to their origin, and their subdivisions now number some hundreds of thousands of stratigraphical names – that is to say, names

for particular rock formations in different parts of the world, each from a particular locality or region.

*The age of rocks*

The whole science of stratigraphy, then, could be developed without any reference to the actual number of years taken for the rocks to form. But this question was never far from the minds of geologists, and many estimates were made of the time involved. It was Hutton who first saw that it must have taken a very long time for rocks to be laid down, hardened, uplifted, folded, possibly intruded by granite, and then eroded with the slow formation of landscape, all accompanied by further deposition – a cycle which he knew must have been repeated many times in the history of the earth. Darwin, too, realized that the immense variety of life on earth could not be accounted for by his theory of natural selection unless there had been sufficient time for the long process to work itself out in detail. Millions of years certainly seemed necessary for this, and the earlier belief that only a few thousand years had passed since the creation became hardly reasonable.

Towards the end of the last century estimates of geological time were made in two new ways. One of these was based on the amount of salt in the sea, and it was thought that an estimate might be made of the length of time taken for it to accumulate. This would be done by finding out the amount of salt carried down by the rivers all over the world, which could be estimated reasonably well, and by calculating the amount of salt in the oceans – which would be done quite accurately, since the composition of sea water is fairly uniform and the depths of the oceans were well known by the end of the century. It was not sufficiently realized at that time, however, that so much salt had crystallized out of the sea to form great salt deposits. Some of these deposits, of course, have been dissolved again and returned to the sea, but many are known to lie at great depths in the earth's crust. Striking evidence of abundant rock-salt exists in the form of SALT DOMES or salt plugs, which have slowly floated up through the rocks to the surface, as masses of solid salt, rather like igneous intrusions. Those of the Gulf region in the Mississippi Plain are amongst the

Diagrammatic section of a salt dome. The central mass of salt was once deposited as a horizontal bed many thousands of feet down, but being lighter than the country rock it has slowly "floated" up through it, like a bubble of oil in water, and in so doing has tilted the surrounding rock. These structures are much sought as possible traps for oil in strata otherwise quite flat.

best known, and the great masses there may have come up from depths of 20 or 30 thousand feet. Any estimate of geological time made from the amount of salt in the sea, then, is likely to be too small.

Another early attempt at an estimate of age was made by assuming that the earth had been formed as a ball of molten fluid from incandescent gas, and then estimating the time it would have taken to cool, using available calculations of the amount of heat lost from the earth. According to this estimate the earth could not be more than 90 million years old, otherwise it would be much colder than it is. But this calculation depended on a number of assumptions about the amount of heat lost and the rate of cooling at the surface of the earth, and it was made in complete ignorance of the important part played by radio-activity. We now know that radio-active materials have been

generating heat all through the ages, so that without knowing how much radio-activity had been going on, and without being sure as to how the earth originated, this method was misleading.

Radio-activity has, in fact, provided the real answer to the problem. It is very difficult to affect the rate of disintegration of atomic nuclei by any ordinary chemical or physical processes, and for some time it seemed as though this was beyond all control. Only recently has some degree of control of nuclear action been achieved, and this under extreme artificial conditions which could hardly have occurred in the history of a solid earth. In general we may take it that the rate of decay of uranium and other radio-active elements has been constant, and quite independent of temperature or pressure or chemical environment. The problem is simply to find some way of measuring their rate of decay – which has now been done in the laboratory with some accuracy – and to apply this to finding out the age of the rocks.

At first it was found that certain minerals in igneous rocks contained a proportion of uranium or thorium, which on disintegration gave rise both to helium and, after a series of changes, to lead. It was assumed that the mineral in which the uranium was contained (the small crystals of ZIRCON within mica in granites, for instance) would have had no lead in it in the first place, and that any lead or helium found in the crystal at a later stage would have been formed during the history of that crystal. In order to determine the proportion of helium, lead and uranium from such small quantities as are found in these crystals, the most delicate chemical tests were necessary, and only a few minerals and rocks with large enough samples available could be used.

But the results of these determinations were very significant and, for the first time, a definite idea of the time scale at the back of earth history began to emerge. Estimates based on the proportion of helium to uranium tended to be too low because some of the helium gas had leaked away during the millions of years it was forming. Estimates based on the proportion of lead to uranium were chemically more reliable, but the age sometimes seemed too high, partly because there had been some lead there in the first place. The idea is simply that

uranium (and thorium) turns into lead at a constant rate, and if the ratio of lead to uranium can be found, the age at which the uranium-bearing mineral crystallized will give the age of the rock in which it was first formed – provided that the rock is an igneous one.

As with most new discoveries, there were many difficulties in applying this method, but it slowly became clear that the lapse of time from the Cambrian to the present day was something like 500 million years, and that some of the Precambrian rocks were very much older than this.

New and better methods have since been devised for using the rate of radio-active decay to determine the ages of rocks. The study of the different kinds, or ISOTOPES, of any one element has shown that in the case of lead some kinds might have been formed from uranium, and some from thorium, while some, perhaps, were originally in the earth as lead. Throughout the history of the earth, the proportions of these different kinds of lead must have been slowly changing, and so, by a very accurate analysis using a MASS SPECTROGRAPH, it is possible to estimate fairly accurately the age of a lead ore by its isotope ratio.

One trouble has been that very few rocks whose age we want to know are closely associated with lead ores, so an intensive search has been made to find whether this method can be applied to some more common mineral. At this moment results from the study of slight radio-activity in POTASSIUM seem to be the most promising. It may even be possible to find the ages not only of igneous rocks, but also of some sedimentary rocks, and this would be a great advance.

The chart shows some of the ages of geological systems estimated by radio-active determinations (sometimes known as RADIO-DATES). All the dates used are still suspect and may have to be increased somewhat. However, for correlating the rocks of the last 600 million years (that is from the Cambrian period onwards) fossils are still far more accurate than radio-active methods. If we wanted to compare the age of a limestone in America with one in Europe, we should get a more accurate estimate by comparing two fossiliferous specimens than we could by any present radio-active method. On the other hand, in Precambrian rocks fossils are rare curiosities, and we are dependent

# GEOLOGICAL TIME

## CHART 4

| Life | | Era | | Period | Age in years | Mountain-building events in U.S.A. |
|---|---|---|---|---|---|---|
| Sea | Land | | | | | |
| | *Man* | CENOZOIC | Quaternary | Recent | 10,000 | |
| | | | | Pleistocene | 1,000,000 | *Santa Barbaran Orogeny* |
| | *Age of mammals* / *Modern forests and grasslands* | | Tertiary | Pliocene | | |
| | | | | Miocene | ? 24,000,000 | *Antillean Orogeny* |
| | | | | Oligocene | | |
| *Nummulites* | | | | Eocene | | |
| | | | | Paleocene | 70,000,000 | *Laramide Orogeny* |
| | | MESOZOIC | | Cretaceous | 135,000,000 | *Nevadian Orogeny* |
| *Ammonites* | *Age of reptiles* | | | Jurassic | 180,000,000 | |
| | | | | Triassic | 225,000,000 | *Appalachian Orogeny* |
| | | PALEOZOIC | Upper | Permian | 270,000,000 | *Arbuckle Orogeny* |
| *Fusulines* *Corals* *Crinoids* | *Important coal forests* | | | Carboniferous: *Pennsylvanian* | | *Wichita Orogeny* |
| | | | | Carboniferous: *Mississippian* | 350,000,000 | |
| *Freshwater fish* | *? Earliest land plants* | | | Devonian | 400,000,000 | *Acadian Orogeny* |
| | | | Lower | Silurian | 440,000,000 | *Taconian Orogeny* |
| *Graptolites* | | | | Ordovician | 500,000,000 | |
| *Trilobites* | | | | Cambrian | ? 600,000,000 | |
| *Marine algae* | *Earliest rocks with ? algae* | (PROTEROZOIC) (ARCHEOZOIC) | | *Pre-Cambrian not yet divided internationally* | 2,500,000,000 | *Many Pre-Cambrian Orogenies* |

almost entirely upon radio dates in a much longer time span. It will be remembered, however, that although fossils may be reliable for correlation, they do not by themselves give any indication of age in years. So we have two quite different methods of giving the age of a rock – one in terms of years, from radio-active dates, and the other in terms of stratigraphy, from fossils. Taken together they give the essential background to most of our thought on the history of the earth.

Whichever method we use will give us only the age of the rocks themselves, and it remains to consider how much older the earth is than the oldest rocks in it. However, astronomers fortunately agree with geologists in placing the origin of the earth at some time before the oldest known rocks, so that there seems to be no real conflict on this point. Some meteorites give radio-active ages of round about four billion years. The age of the oldest rocks is just a little less than this, and the age of the earth is thought to be a little more. But any detailed knowledge we have of the history of the earth covers only the last 600 million years, and man has been present for less than a million years, from the time of the Great Ice Age onwards. Man himself, then, belongs to the very latest part of the history of the world, and his civilization falls within the last ten thousand years, which we know geologically as the RECENT PERIOD.

For more than a hundred years rocks have been correlated (i.e. compared for age) by their fossil content, and on this basis the geological systems were defined. Each system of rocks is said to have been formed in a period, thus the Jurassic (system of) rocks were formed in the Jurassic Period. Each system of rocks is defined by a particular range of fossils, as are its many subdivisions (not shown in the chart). Similarly, the periods are grouped into eras according to the general stage of development of life, and some characteristics of the eras are indicated in the left-hand column.

The age in years is simpler to understand, but far more difficult to determine, since it depends on elaborate assumptions and experiments which can be made so far on only a limited number of rocks – mostly unfossiliferous. However, these radio-active ages are the only means we have to give a scale in years to the geological periods. Often the radioactive dates are determined from igneous rocks associated with mountain building events, so the relation of these earth movements to the geological – or stratigraphical – column is critical.

Good zone fossils may correlate to within one or two million years, but they do not give an age in years at all. Good radio-dates may be accurate to within, say, 5 or 10 million years. Most fossil or radio ages are far less accurate than these.

# *Part 4*

# THE WEALTH OF THE EARTH

## 13. Wealth and beauty

Man, like other land animals, depends on water and soil, without which life would be impossible. As civilization has developed, materials other than food have become essential to his way of life for building or manufacture, or for heat and power. We tend to take all these for granted now, but they are all in limited supply.

To find them requires some geological knowledge, and to plan their proper use depends on some estimate of future supply. Supplies essential to industry in general will be outlined in Chapter Fifteen. Wealth, however, is something more than economic power and the necessities of subsistence. We do not use our knowledge of the earth's structure merely to exploit its resources. For those who are alive to the wonder and variety of rocks, minerals and fossils, there is an unending wealth of interest and a growing sense that we live on a very wonderful earth. Indeed, one of the greatest kinds of wealth is the beauty of the world as we find it – a beauty which is strengthened by a knowledge of the structure underneath it and by the immense time it has taken to become what it is, and by the prospect of an equally long future.

Notions of value or beauty change. Once kings or nations were considered wealthy only if their treasures held stores of gold, SILVER and precious stones. Today the great importance of the DIAMOND is in industry, because of its hardness. It can be ground up as a powder and used to cut almost any other material, at great speed. Silver, too, is an important raw material, used in the many and complicated pro-

cesses of photography. But for many centuries the precious and semi-precious materials were valued simply for their inherent attraction.

*Gold*

The noble metals, as they are called, are those which resist rusting and corrosion and consequently retain a bright and shiny surface and a rich metallic lustre. Of these metals, gold and silver are the best known, and have long been used as a standard of wealth and as a basis of exchange. Although today we find paper money and bank accounts more convenient, many economic problems were much simpler in the days when gold and silver alone were acceptable: silver dollars and golden guineas maintained their value independently of the fortunes of princes and governments, and could be stored and accumulated as wealth – as they still are in many parts of the world.

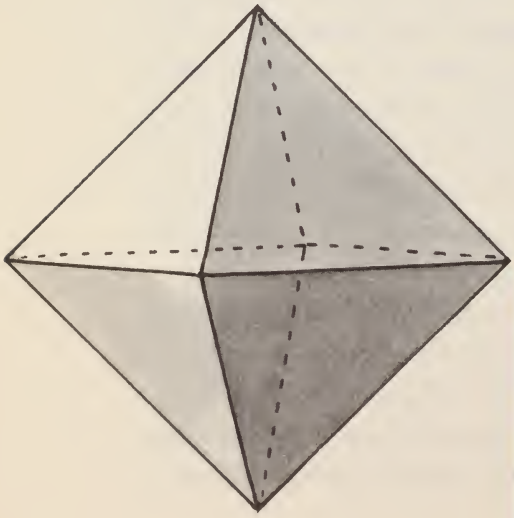
One reason for the early importance of gold was simply its noble nature, which, resisting chemical attack by air and water, made small particles of the metal easily distinguishable. Gold commonly occurs in quartz veins among igneous and metamorphic rocks, and where it is mined today – as in South Africa – many tons of rock are crushed to extract a few ounces of gold, but this way of mining is only possible with modern machinery. However, where original gold-bearing rocks have been subject to erosion, the gold-bearing gravels and sands have been washed down the streams and rivers, and the rattling of pebbles against each other has separated the fragments of quartz and other minerals from the gold itself. Gold is very dense, so it is not washed away as quickly as the other fragments. It is also malleable, or ductile; on being crushed between boulders it does not crack or break up into smaller pieces but merely bends slightly. In this way any gold which is washed down a stream will tend to be preserved with the gravels and not get carried out to sea.

It was in these river gravels and sands that gold was first discovered. In each river which had gold the first person to look was the luckiest, and by the time of Christ most of the easily accessible gold-bearing gravels had been searched for the larger particles, or nuggets. The wealth of Solomon, and of many other great kings of the Old World,

was gathered together from the findings of individual men seeking for themselves in the sands and gravels, often using a small basin or pan to swish around the water, throwing out the less dense minerals and so concentrating the gold dust at the bottom. It was this same simple method which led to the gold rush of western America during the last century, when, in the rivers of the newly inhabited areas, some remote settler would make a new find – using only a spade, a bowl, and a good pair of eyes.

The largest nuggets of gold which have been found weigh many pounds, but most of the gold accumulated in the strong rooms and vaults of the nations has derived from very small particles, or gold dust, scattered throughout hard rocks. It was found long ago that gold adhered to certain oils and greases such as are found in the wool of sheep – hence the legend of the Golden Fleece. These properties are used today in industrial processes.

The occurrence of many other precious materials also depends on this same process of concentration in river gravels. When the minerals are resistant to chemical change, mechanically strong, physically hard, and also denser than the ordinary pebbles and grains of sand, they will tend to remain and be concentrated in river deposits. River deposits are known as alluvium, and such minerals as are found in them, whatever their original source are described as alluvial.



Diamond is the hardest mineral known, and one of the most valuable. It is a crystalline form of pure carbon, as shown in the left-hand diagram. The elaborate shape of the typical gemstone, as shown on the right, is the result of artificial cutting and polishing, designed to give the best internal reflection and greatest brilliance.

An impression of a South African diamond mine. Diamonds are found in kimberlite, a soft clay which occurs in pipes or vents reaching into the depths of the earth, where pressures were great enough to form diamonds.

*Diamonds*

The diamond is one of the most precious of gems, and is made of pure carbon. Carbon is one of the principal elements in all living matter, a very important part of coal and oil, and abounds in the calcium carbonate of limestone. It is also widespread throughout the face of the earth in the carbon dioxide of the air. Carbon as an element may occur in various forms. One common occurrence is GRAPHITE – a black, soft greasy substance used for lubrication and for "lead" pencils. Graphite is one crystalline form of pure carbon, and if this material is subjected to enormous pressure it will change its crystalline form into one which has a much closer packing of the individual carbon atoms, and consequently a higher density – the result being a diamond, which is the hardest substance known on

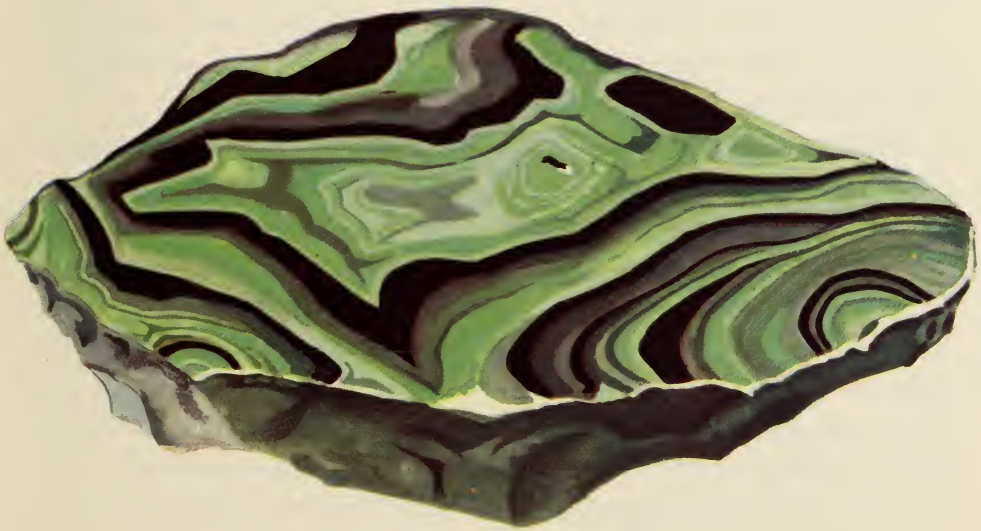
earth. The diamond is valued partly because of its hardness, and partly because of its clarity and brilliance in reflecting light. As normally seen in jewelry it has been cut and polished so as to present a number of flat surfaces making an attractive geometrical pattern and designed to reflect light in such a way as to give the utmost sparkle. A natural crystal of diamond is a much simpler shape, being an ordinary octahedron with somewhat rounded corners and faces. Like a number of other precious minerals, the diamond was originally found in sands and gravels, but in South Africa it is also mined directly from the original rock in which it occurs. This is found in great pipes thousands of feet across and stretching for many miles down into the earth. The blue earth, or clay, in which the gems are found is very soft, and there seems little doubt that the rock as a whole has been forced up these pipes from the depths of the earth, for it is quite clear that diamonds can only form under the very greatest pressures. It remains a mystery, however, as to how these intrusions, or diamond pipes, originated.

The diamond is most valued as a jewel when it is colorless. Other gemstones are characterized by distinctive tints. The red RUBY and blue SAPPHIRE are examples of these valuable minerals which, when polished, make brilliant gems of great hardness.

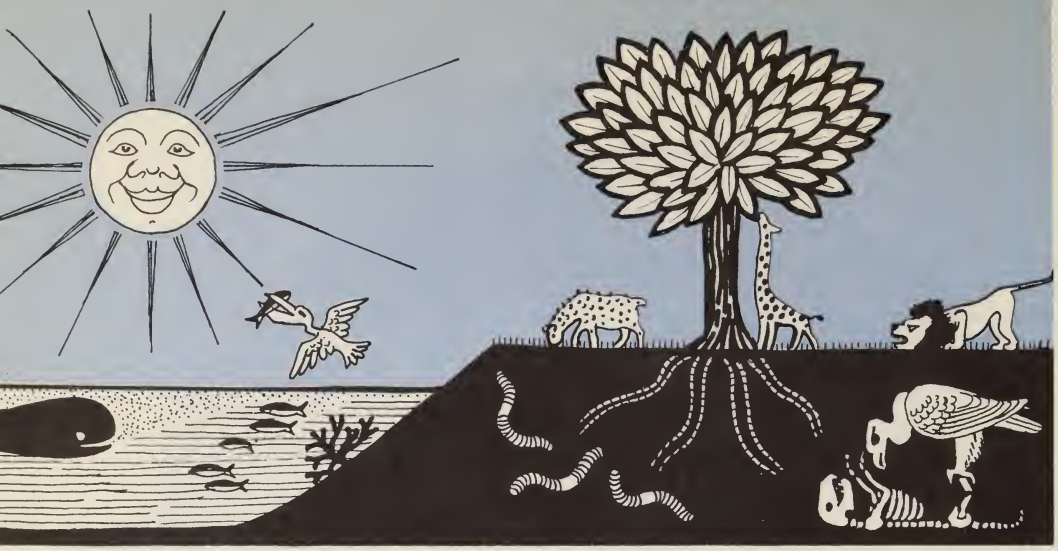
*Semi-precious stones*

There are many other beautiful minerals which are not so rare, and therefore less valuable, but are much appreciated nevertheless. Garnet is quite a common metamorphic mineral and some forms of it have a rich reddish color. MALACHITE – a hydrated carbonate of copper – is of a beautiful greenish color and is often used for brooches or small carvings. Among the many other colored stones of great beauty but of no great value are various forms of silica. CHALCEDONY is one form of silica which is not obviously crystalline and has a peculiar milky luster. AGATES, whose rich variety of color is largely due to natural staining (though staining is sometimes artificial), are formed in the cavities of rock, from percolating waters. The cavities may be the VESICLES, or gas bubbles, in a lava and the agate is formed afterwards in layers, lining the cavity and sometimes filling up the hol-

Agate is a form of silica (chalcedony) which is now known to be made of ultra-microscopic quartz crystals. It grows at low temperatures, and commonly in cavities, from silica-bearing water. The illustration shows the banding typical of a cavity-filling agate in which the growth occurs from outside inwards, and the colors are due to staining at each stage in growth.



Malachite is a colorful green copper mineral. It is an attractive material for small ornaments, but not of any great economic importance.



The illustration reminds us that all animals live by eating other animals or plants while plants alone, using the energy of sunlight, are able to manufacture (photo-synthesise) their own organic materials from carbon-dioxide, water and traces of mineral matter in solution.

low with a horizontal layered pattern. If these so-called AMYGDALOIDAL agates are in a basalt, they will be much harder and more resistant to weathering than the basalt, and so will tend to fall out and collect as pebbles when the basalt wears away. These pebbles look very ordinary at first sight but on breaking or sectioning may show fine colors and patterns, and the material is hard and tough. Brooches, snuff boxes, and various small ornaments may be carved from it.

Perhaps one of the finest stones for color, texture, and carving is the mineral or rock known as JADE. It is a complex silicate and may be milk-white, yellowish, or as it is best known, green. Some of the most wonderful carvings from the ancient Chinese civilization are of jade. The seals and other tokens of office of the highest ranks were of this material, and anyone who has a chance to examine good jade ornaments will appreciate the sensibility of the early Chinese.

For centuries these materials were valued for themselves alone – for their durability, their resistance to rusting and decay, and above all for their beautiful appearance. The value that has been set on these metals and stones is also due to their scarcity, and from a geological point of view they may therefore be of least interest in understanding the history and working of the earth.

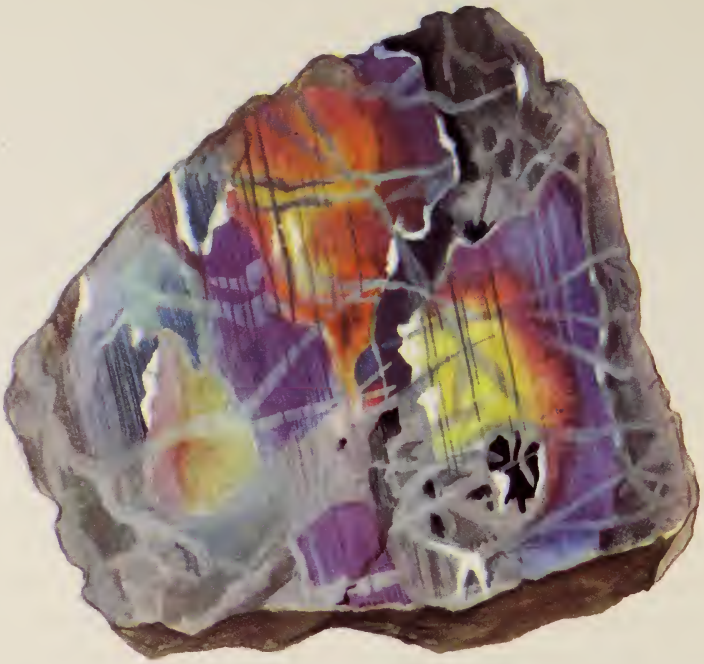
# 14. The water of life

Water is one of the most familiar and yet one of the most remarkable substances on the surface of the earth. It has a greater capacity for storing heat than any other common material. Unlike most fluids it is heavier in its liquid than in its solid form, so that ice floats on water instead of sinking. If it were not for this the Arctic Ocean might now be solid, and marine life as we know it would have been quite impossible. There are very many other properties which together make water a unique substance and the basis of life. All animals and plants need water, and the distribution of water around the world determines, to a great extent, the pattern of life on its surface. It is now known that almost every element is necessary to life, even if only in minute traces, but water is usually the limiting factor because where there is sufficient water the other materials are usually in adequate supply too.

There seems little doubt that life originated in water, possibly in the sea, and it may only have been at a late stage in evolution that life established itself on dry land. The development of animal life on land must have been preceded by plant life, which in turn depended on the water supply and the nature of the soil supporting it.

*Soil*

Most of the surface processes of erosion depend on the water cycle, by which we mean the continuous process of evaporation of water from the sea and its transport by winds over the continents, where, under cooling conditions, rain or snow is precipitated and returns in due course to the sea. When rain falls on the ground, some of it immediately evaporates back into the air. Some, known as the RUN-OFF, trickles over the ground down into streams, and may be very destructive of the soil, cutting deeply into the landscape and charging



Labradorite is one of the many varieties of plagioclase feldspar. Most feldspars (and most labradorite) are white or colorless when seen in rock, but some large crystals of labradorite show a beautiful iridescence. Rocks bearing this kind of mineral are thus valuable ornamental stones.

the streams with débris. Most of the rainfall, however, sinks directly into the soil. In temperate climates it is only after exceptional rain that water runs directly off the surface, for the soil seems to be capable of absorbing a great deal. The organic matter in soil, known as HUMUS, as well as the clay material, has a much greater capacity for holding water than any ordinary rock or sand. So a surface layer of soil will accumulate water and encourage the growth of plants which will tend to hold the layer together by their roots, protecting it from immediate erosion.

This thin layer of soil is therefore very important to the whole economy of nature. In the past its importance was often realized too late when, in dry regions, the land was over-grazed or over-cropped, reducing the organic content of the soil and leaving it more vulner-

able to erosion. In the United States the early settlers raised good crops during their first few seasons, but when the organic content of the soil was reduced, in those areas where the rainfall was very small still less of it could be kept in the soil against the periods of drought. A large proportion of the rain, therefore, ran off the surface, causing sheet and gully erosion, biting deeply into the prosperous farms and creating "BADLANDS". During periods of drought, when the lack of moisture in the soil failed to hold it together or encourage plant growth, the soil crumbled into a fine dust. So the most valuable top layer of the soil, if not washed away by the heavy rains, was often blown away in times of drought, and the accumulation of many centuries was destroyed in a few years through ignorance.

This scourge of soil erosion has affected many parts of the world where civilizations have flourished and then decayed. Some of the ancient civilizations may have declined simply because of too prodigal use of their soil, and many parts of the earth which are now desert show abundant evidence of former occupation by man in times of great prosperity. Parts of the desert north of the Sahara were once

Opal is a form of silica with up to 10% water. Like many semi-precious minerals, its value depends on the accidental effects of growth and impurity, and precious opal displays a delicate range of colours.

Contour plowing is necessary in many dry regions to prevent soil erosion after rain. Furrows up and down hill allow streams to form, which may wash away the soil, whereas furrows which are plowed horizontally hold the water until it can sink into the ground.

rich wheat lands supplying the Roman Empire. In the Sind Desert of north-west India are many ancient monuments, indicating more populous conditions in the past, and in north-western China the famous loess regions, once the cradle of Chinese civilization, have suffered from erosion and depopulation throughout the centuries.

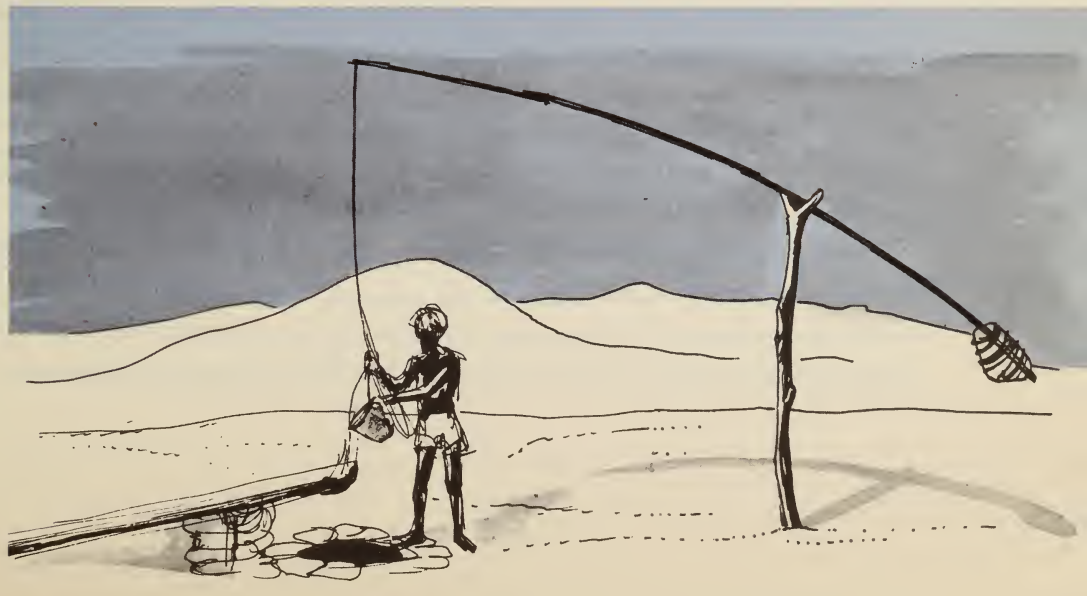
Today we appreciate the value of this top few inches of soil, and all over the world active steps are taken against soil erosion. The farmer is familiar with contour plowing, which takes a level course round the slopes instead of straight lines up and down. This enables the water to accumulate in small pools in the furrows and sink in, instead of running off downhill. In strip cultivation, alternating strips of growing vegetation – perhaps even forests – are retained between strips of arable land, so that water cannot flow far over the surface, nor can the wind blow over it quickly. Dams are built in valleys so as to hold back the water in flood time and allow the sediment to settle, and to form a reservoir for use in times of drought. Deforestation has often started soil erosion in the past, but nowadays reforestation is often used as a means of restoring a proper water supply and establishing the

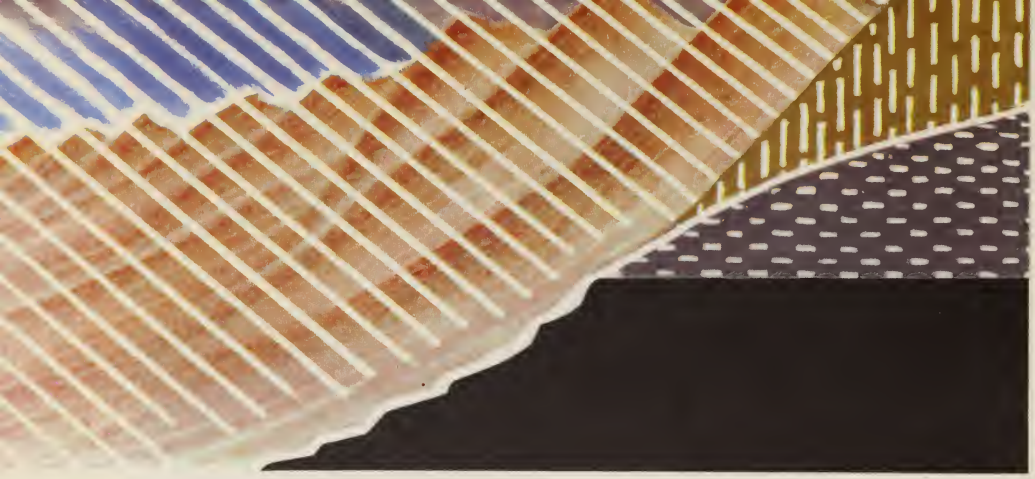
soil again. In truly desert regions very few plants can grow without artificial irrigation, but it is possible that whole new areas of the earth's surface may eventually be developed for food production if sufficient power and resources can be put into the irrigation of desert lands.

*Ground water*

With the growth of industry, man has developed large cities whose populations use enormous quantities of water, averaging 40 to 100 gallons a day for each individual, and even 200 gallons a day with particular needs. In some areas all these demands can be met easily by tapping some large river, and in regions of high rainfall there is also no difficulty. Elsewhere man is dependent on the supply of what is term GROUND WATER. Rain water as it falls is first stored by the soil and then seeps downwards into the ground, permeating some rocks (limestones and sandstones) much more than others (CLAYS). These PERMEABLE ROCKS, as they are called, which allow water to pass readily through them, may be constantly flooded by water from above, and at a certain depth they will be full up so that the water can no longer flow downwards. At this level we have what is known as the WATER TABLE – that is to say, the surface in the rocks below which the rocks are full of water, and above which there is some air

In many of the old world desert regions irrigation from shallow wells is carried out, as it has been for ages, by the simple method shown above. Increasingly today, however, deep drilling and powerful pumps are depleting the underground reservoirs of fresh water at an alarming rate.

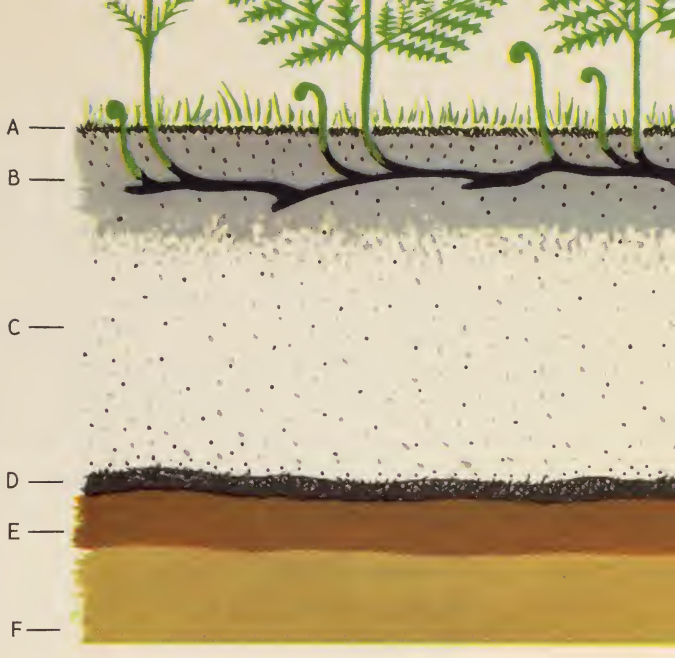




The rain falling on a hillside seeps down until it comes to where the rock is fully saturated with water. The top surface of this is known as the water table, and is seen to slope less steeply than the hill. Where the water is held up by an impermeable rock the water table meets the hillside and water flows out as a spring.

as well as water. The water table, unlike any free surface of water in the open, is not flat. Beneath a large hill, for example, the water table may itself take the form of a small hill, with the water seeping very slowly down its slopes to the bottom. If the water table is only a few feet beneath the ground, wells dug below the water table will fill up to just that level. In this way man has supplied his immediate needs for many centuries, but with modern drilling water can now be pumped from much lower levels than used to be possible. If too much water is taken from a well, however, the water table will fall and the whole area will be slowly depleted.

In some places the permeable rocks may be covered by impermeable ones through which the water cannot pass, but if their surfaces are exposed to rain in highland areas, the water may percolate down through them and form RESERVOIR ROCKS beneath the plains. The water in these reserviors may be under great pressure because of the height of the mountains where the rain fell, and if the overlying impermeable rock is punctured by a well the water will pour out with considerable force. Such wells are known as ARTESIAN WELLS, and a basin in which artesian water may be found is known as an artesian basin. Water of this sort has helped to supply the deserts of eastern Australia,




Section through a natural soil profile showing the different layers which develop from percolating waters. This one, a podsol, is typical of cold temperate moorlands on sandstone.
A: layer of black peat; B: leached sand (grey with peat); C: leached sand (white); D: humus (black vegetable matter); E: iron oxide concentrate (iron pan); F: unaltered sandstone.

and for many years the City of London's supply came from artesian water trapped in the chalk layer lying beneath the city itself but exposed to rainfall at the surface in hills round about.

*Streams and rivers*

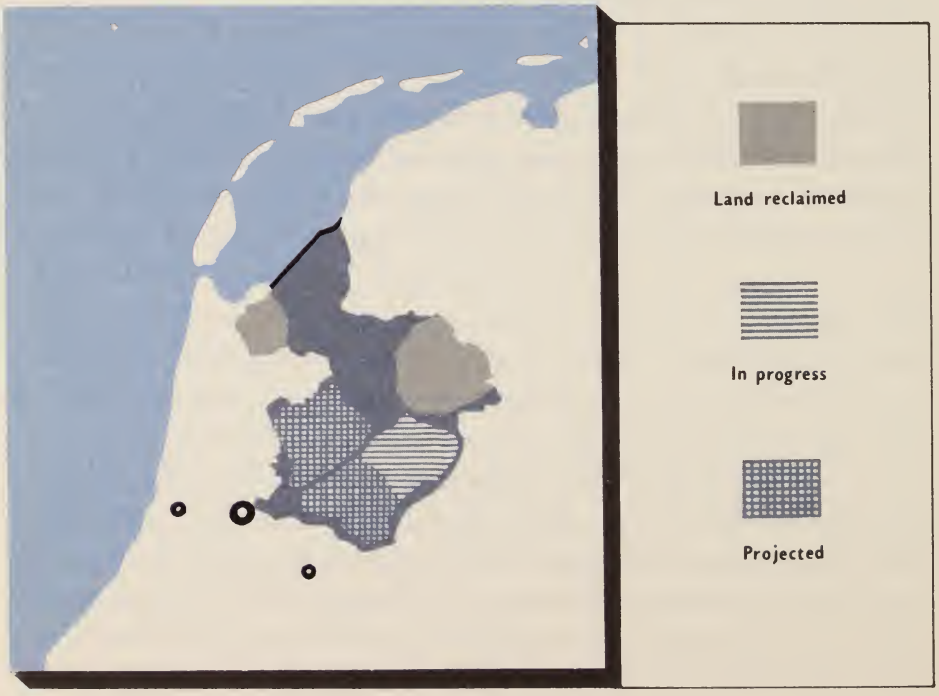
When water is not taken from wells, the water table will rise slowly either until it meets an impermeable rock and is placed under pressure, or until it reaches the surface and flows out from underneath the soil as a SPRING. Most rivers begin in this way, from a steady supply of ground water, further ground water being added as they flow along their course. In temperate climates we are accustomed to rivers flowing throughout the year, regardless of rainfall. This occurs because their supply comes from stores of ground water replenished from time to time by rain. In desert regions, on the other hand, where very little water is absorbed into the ground, the rivers may flow in great torrents after heavy rain, only to cease as the rain itself stops. Some desert regions have the same amount of rain as regions with slight vegetation, but in the desert the rain as it falls runs off and passes out of the area, what little there is left being quickly evaporated. In areas where there is some soil cover the rain is largely absorbed into the

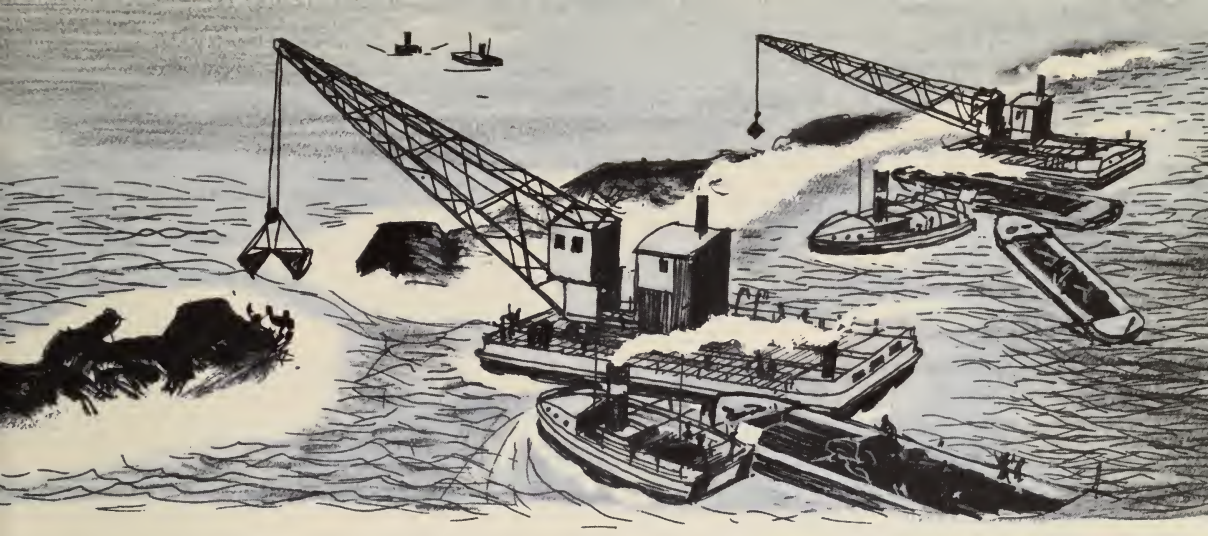
ground and flows out in a more gentle stream over a long period; the ground thus acts as a gigantic reservoir and tends to even out the flow of water in the rivers, or in wells.

*Flood water*

Most civilizations have developed in the flood plains of great rivers. Under natural conditions a meandering river will change its course, from time to time, especially if sediment builds up the level of its channel above the surrounding plain. But since the frequent changing of a river course is inconvenient to man, the river banks have been strengthened and heightened to prevent frequent flooding. The result of this has been that when the banks have burst in times of exceptional flood, the floods have been more serious because they were unexpected and because the river level had been slowly built higner. Fortunately

Sketch map of Holland showing the old Zuider Zee, which was isolated by a dike in 1932 to become the freshwater Ijsel lake, from which large areas of land (polders) are reclaimed by building dikes and pumping the water out. The map shows progress in reclaiming polders already made by 1955.





An exciting stage in the building of a dike in Holland. The grabs are filling the remaining gaps with material carried by barges, which may have been taken from the positions where canals are projected. Nowadays elaborate pumping machinery fills the barges from the lake bottom and empties them on to a wide dike.

these difficulties may be overcome in various ways. For instance, if a MEANDERING river is straightened it can be kept more easily between its banks, since the straight river will flow more rapidly down the steeper gradient and so keep its channel clear of sediment. This is particularly important if a great river is used for navigation. Another device is to prepare safety flooding areas into which the peak flood waters can be diverted, reducing the pressure on the main part of the river. These areas may still be used for farming, but no dwellings are built and no livestock kept there in danger periods. The ultimate attack on flooding, however, is made near the source of a river, and goes hand in hand with soil conservation. In this part of a river's course, reforestation on the river banks will produce a more even flow throughout the year, and prevent extreme flooding. Great dams, too, will contain the heavy rain waters and release them when they are needed, and so surface reservoirs are added to the natural underground reservoirs in the rock.

In addition to the essential part it plays in sustaining life, water may also be used as a source of energy. As such, it is virtually inexhaustible, and water power is one of the great assets in the long-continued maintenance of industrial civilization.

Diagrammatic section showing an artesian well. The city rests on impermeable rock overlying a syncline, or basin, of pervious rock which outcrops in the surrounding hills. There the rain replenishes the ground water, which flows naturally from the well under pressure due to the higher water table in the hills.

*The struggle against the sea*

In Holland much of the land is below sea level, and to find more land for a growing population great dikes or walls have been built against the sea, the sea water has been pumped out and the original sea floor cultivated. In this process fresh water must first wash the land free of salt, for crops will not grow in saline soil. Indeed, if too much fresh water is taken out of the ground for industry, drinking, or irrigation, the pressure of the sea water outside will force salt water up into the ground and destroy the fertility. The Dutch thus have a constant struggle not only against the sea along the dikes, but also against the salt water beneath them at no great depth. To combat this they have developed an ingenious system of waterworks, in which freshwater from artificial lakes is carried round the fields by canals, and so balances the pressure of the sea water outside and underneath.

However, the sea is not, after all, an enemy to man. It encroaches on his land, but it gives rise to the rain which, owing to the energy of the sun, is a source of life and power – and in a future nuclear age we look to the sea as an inexhaustible source of power and water.

# 15. The material basis of industry

The way industry has developed in different countries has to some extent been governed by the natural resources available for it. New processes, however, keep making more and more of the natural resource of the earth available to man, so areas once poor in mineral wealth may, in a later age of advancing technology, become rich.

Materials which are taken for granted in most parts of the world may be very scarce in certain places. In many tropical countries where the rainfall is heavy, places far from the sea are desperately short of ordinary salt. The great earthworks or dikes in Holland, built to keep out the sea and contain the lakes, are built in areas where everything is soft mud and sand, and there is no hard stone to hand. The hard stone, so common in most parts of the world, has to be imported by barge from Germany, for the bricks of which Dutch houses are built would be far too expensive for the miles and miles of sea defences.

*Building materials*

The development of civilization would be impossible without materials for buildings, roads, bridges and storage containers. There are three kinds of building material and they are often needed in very large quantities, so they must be common rocks and not rare minerals. First are the hard stones which are quarried for building, for making carvings, for breaking up and using as ballast in railroads and for highways. Igneous rocks are usually the hardest and the most useful for crushing up for ballast and road "metal", and they often make the most durable buildings, too. However, they are often too hard to work easily, so that limestones and sandstones are usually preferred for building. Many of these rocks are naturally bedded and jointed, so they can be quarried in slabs convenient for building with very little dressing.

A rock which can be chiseled and carved easily, without breaking up or splitting, is known as a FREESTONE. Rocks of this sort are particularly favored for buildings such as churches, where there is much use of carving. Other stones are valuable because they do split very regularly, and can be used as flagstones for pavements and as slates for roofing. Flagstones are usually sedimentary rocks, such as sandstones, which were deposited in a number of fine layers, and can be split easily along these original strata. Splitting is helped by innumerable small flakes of mica in the rock, parallel to the bedding. The best roofing slates, on the other hand, have a rock CLEAVAGE which generally does not run parallel to the bedding. As a rule such slates were originally mudstones or clays, made up of the finest clay particles, and have been turned into slates by squeezing under tremendous pressures deep down in the earth.

The second kind of building material is simply fine clay or silt, which can be baked and made into bricks, pottery or china. In hot dry countries bricks can be made by mixing this with water and sometimes a little straw, shaping it in wooden moulds and then leaving it out in the sun to dry. Hard bricks are formed which can be built into a wall, using mud as a mortar. This is a very cheap and effective method for small buildings, which was used in the Middle East from earliest days, and is still used in many parts of the world. If, however, the bricks are baked, chemical changes take place and new silicate materials are formed which are very resistant to weathering, and mechanically very much stronger. Most civilizations have depended on bricks, at least for larger buildings, even if timber has been used for the smaller ones. With the finer clays, tiles and pots and many other shapes could be fashioned and baked. So, given a fuel supply, peoples in the river plains, with no hard rock, could make most of their housing and hardware out of the local river mud.

For making large brick buildings, something better than mud is needed to cement the bricks together, and this is the third important building material. It was discovered long ago that by burning limestone, QUICKLIME was formed. This quicklime readily unites with water to form slaked lime, which becomes hard when, in the course of

time, carbon dioxide from the air reacts with it to form calcium carbonate again – which is not very different from the original limestone. In the early days quicklime was mixed with sand, and was quite suitable for use in dry climates. However, just as limestone may dissolve, so this man-made mortar was also liable to dissolve and allow the bricks to break apart. Finally, a much better material known as CEMENT was produced, and this is what is nearly always used nowadays. Cement is made by mixing together mud and limestone, very finely ground, and heating them in a kiln. Quite often the appropriate mixture of clay and lime occurs naturally as a MARL. When it is heated, a series of complex silicates is formed, which, on combining with water, form very resistant materials, less soluble than limestone. By varying the ingredients different cements have been made, many of them exceedingly tough, and some capable of hardening under water.

One of the chief developments of our time is the production, in enormous quantities, of good quality cement, which, when mixed with sand and gravel, makes CONCRETE – and concrete may be just as important in this century as brick-making has been for thousands of years. Good cement was used by the Romans but vast quantities are now made by means of large-scale machinery, by which sand and gravel are obtained in bulk, carried over great distances, and mixed with the powdered cement in huge mechanical mixers. With the discovery that it can be strengthened by enclosing rods and strips of steel, concrete has become the major constructional material for buildings, roads, bridges, dams, and drainage works. So much of it is used today that near large industrial centers the commonest materials, such as sand and gravel, are exploited wherever they are found.

*Metals*

COPPER and TIN are far more abundant than gold or silver and are not too difficult to smelt. Their ORES, being of a somewhat metallic appearance, were easy to find, and the two metals were combined to make BRONZE, which is harder than either copper or tin and was the earliest ALLOY to be used for tools and weapons in many parts of the world. Copper and tin are now considered far too valuable for ordinary

structural use. Copper is of immense importance because it is one of the best conductors of electricity. ZINC and lead were also mined from earliest times, lead being valued because it was easy to work and was resistant to weathering. Many early church roofs, and modern roofs, too, are made of thick lead sheeting, which is very heavy. Lead was also used for most early plumbing – the word plumbing itself being derived from the Latin for lead, *plumbum*. Zinc is much more common than tin, and is now used with copper to make BRASS, a very common alloy, which is easy to cast in moulds and to shape by machining.

Tin, copper, zinc and lead are often found in the same areas, usually not far from a great mass of granite. It appears that some granites, in their later stages, have given off vapors containing these metals, and the vapors have condensed as mineral veins in the surrounding rock. This MINERALIZATION, as it is called, usually shows a definite order, with tin being nearest to the granite and lead being furthest away. Tin ore is commonly found as an OXIDE, or CASSITERITE whereas copper, zinc and lead ores are usually SULPHIDES, namely CHALCOPYRITE, SPHALERITE, and GALENA.

Another group of metals, occurring in quite different circumstances, includes MANGANESE, nickel, and, most important of all, iron. Iron is very abundant in the earth's crust and modern processes make it economical to extract iron from rocks with an iron content of less than 20%. The richest natural source of iron is found in meteorites, but these are exceedingly rare. Some iron ores are of igneous origin, and the mineral in which this iron occurs is MAGNETITE. HEMATITE, the red or kidney iron ore, is also very valuable but is not found in large quantities, for it has usually been formed by the percolation of iron-bearing waters.

Other IRONSTONES have been formed under peculiar sedimentary conditions which are not fully understood. The important ironstones of the Lake Superior mines represent a great development of Pre-

Impression of an oil field. The section below ground shows a well penetrating the porous beds (or reservoir rock) between impermeable beds in an anticline. Within the pore spaces of the rock natural gas has risen to the top, then a layer of oil which is being pumped, underlain by water on which the oil floats.

cambrian sedimentary rocks which must have formed in rather special circumstances. The most important iron ores of Britain, France and Germany are OOLITIC ironstones with iron silicate minerals, formed under the sea. The rust-colored iron ore, LIMONITE, is formed by weathering and oxidizing bacteria, commonly in swamps and bogs, and may be associated with coal deposits.

There is a great variety of ironstones, the most important of which occur as sedimentary rocks. This illustrates a general principle that materials which are distributed more generally in igneous rocks often become more concentrated in the sedimentary rocks, for iron is very common in all igneous rocks, but is not found in sufficient quantity to make it possible to extract it. Throughout the ages igneous rocks have weathered, and iron-bearing solutions have passed down to the lakes and seas, where they have been concentrated by various processes, under special conditions. It is these concentrations which are now exploited by man. There are only limited quantities of the richest iron ore, but there would be almost unlimited iron available if sufficient energy could be spent in getting it.

Much the same applies to ALUMINUM. In the surface rocks aluminum is even more common than iron, for it is an important constituent of nearly all silicate minerals, particularly of the feldspars. But it is very difficult to separate aluminum from these silicates – even from the weathered products, which are so abundant in the form of clay. The most important aluminum ore is BAUXITE, which is really a special concentration due to tropical weathering of aluminum silicates – a peculiar kind of soil. Another mineral, CRYOLITE, is a rather special aluminum-bearing vein mineral, and is worked in south-west Greenland.

*Chemicals*

Modern industry depends more than ever on the development of chemicals from various basic materials. Coal and OIL, referred to below under the heading of fuels, are important as sources of various carbon compounds. The variety of chemical products derived from these two materials is prodigious, and through the ingenuity of the

chemist new synthetic materials have replaced many natural products. Synthetic fibres, for example, are often used instead of wool and cotton, and plastics have been found more convenient than metals for many light electrical and domestic appliances. The organic chemist has also invented innumerable new drugs, paints and dyes, but like the rest, they depend ultimately on the wealth accumulated in coal and oil. Carbon, which through coal and oil is the basis of so much industrial chemistry, is much more abundant in the calcium carbonate of limestone and in the carbon dioxide of the air. Nitrogen and oxygen in the air, and oxygen and hydrogen in the water, are abundant enough too, but they are far more expensive to use for some purposes than the materials of coal and oil, which have already been made up by the energy of sunlight and living organisms in past ages.

The chemical industry depends also on vast quantities of SULPHURIC ACID, which is obtained in the first place by burning SULPHUR or from sulphide of iron. Rock salt is a source of CHLORINE and HYDROCHLORIC ACID. Indeed there are few rocks and minerals which are not used in some chemical process; the main considerations in selecting them are their purity and availability.

*Fuels*

It is commonly said that we are burning, in our fires, power stations, and automobiles, the fossil fuel derived in the first place from the sun's energy and stored up over millions of years, and that we are burning it up at a much faster rate than it is being replaced. Coal was formed by the slow accumulation of forest products in swampy conditions. Swampy conditions were necessary because, if the dead vegetation were not rapidly covered by water, it would decay and disappear. The organic material, covered by stagnant water with a very low oxygen content, has gradually accumulated (in some places reaching great thicknesses) as a result of a rise in the water level or a gradual subsidence of the land. When overlain by sediment and preserved for long periods, this accumulation has by some slow process turned through peat and LIGNITE to bituminous coal, and eventually to ANTHRACITE.

It seems as though the pressure of deep burial is necessary for the later stages of this process, during which much of the oxygen and hydrogen of the original woody material is lost, leaving a coal increasingly rich in carbon. Tree trunks can sometimes be distinguished in coal, often greatly flattened, and a seam of coal may thus represent a twentieth of the thickness of the original vegetable accumulation. Most coal was formed almost in the position of growth, and at the base of some coal-seams there are tree roots preserved in their original soil. Other coals were formed in the bottom of lagoons from drifting leaves and plant spores.

PETROLEUM, or natural mineral oil, is more widely spread in rocks, but less concentrated than coal. Many sedimentary rocks, particularly those formed under the sea, contain as much as 5% of organic matter which has been incorporated in the sediment. Minute organisms living in the sea are normally eaten or decay, but they may be carried down and covered up quickly by very fine sediments which seal them off from decay. So it is usually in fine-grained marine sediments, often not far from the shore, that organic material, giving rise to petroleum, is found. However, this is only the first stage, for petroleum, before it is of any use to man, has to be recovered from the rock, and only occasionally is it sufficiently concentrated in sands and clays to flow out when reached by boring. Commonly the original organic material migrates from the SOURCE ROCK in which it was formed up to a nearby RESERVOIR ROCK, usually a sandstone or a limestone, which is both more porous and more permeable. Thus when it is punctured by a well and the whole is under pressure petroleum gushes out at the surface. Many limestones and sandstones which have once contained petroleum now show no trace of it, for it will always tend to float upwards on top of the water in the rock if given a chance, and during the course of ages most of it has escaped at the surface.

Petroleum is thought to be largely due to minute marine animals

Impression of a coal mine, showing the coal seam being mined and the coal wheeled to the cage, which hoists the coal up the shaft to the surface. Today the whole process is highly mechanised, both the mining below ground and the handling and sorting at the surface.

and plants, and has nothing to do with coal, but both coal and oil are the result of the accumulation of past living things, preserved by some accident until exploited by man. At the expected rate of exploitation these materials are not likely to last much more than 100 years, and the prospect for future energy requirements would be poor indeed were it not for the recent discovery and harnessing of NUCLEAR ENERGY, and the possibilities of trapping SOLAR ENERGY, with or without the use of plants.

Nuclear energy is likely to be the most important future source of energy to man, surpassing coal, oil and water power. Natural deposits rich in uranium are not very widespread, though technological improvements may make it possible to use poorer grade ores, but it seems almost within the grasp of man to extract a virtually limitless source of energy from the HEAVY WATER distributed throughout the ocean. At the moment nuclear energy is no cheaper than other forms of energy, but if in due course it should become cheap the scale of values of many other natural resources may be altered.

The cost of recovering most materials ultimately depends on the cost of energy. The cost of growing food in deserts depends on providing water, for fresh water can be provided anywhere on the earth's surface if energy is cheap enough to distil sea water and pump it to the desert. The prospect of cheap energy in the future will make us adjust our scale of values once again, as it has been adjusted over and over again in the past, and lead us to reassess the possible uses to which the immense resources available to us may be put. New materials for construction, new chemical processes, and new methods of food production will almost certainly be developed.

Only when thinking in terms of geological time must man seriously consider whether he is using up irreplaceable resources. For he is tending to take natural concentrations of valuable materials and disperse them. Many of these concentrations are being dispersed much more quickly than they accumulated. At the present rate there will come a time when much that is now common will become rare. At the same time other materials will achieve a new value. The world's wealth as we see it is relative to our need.

# *Part 5*

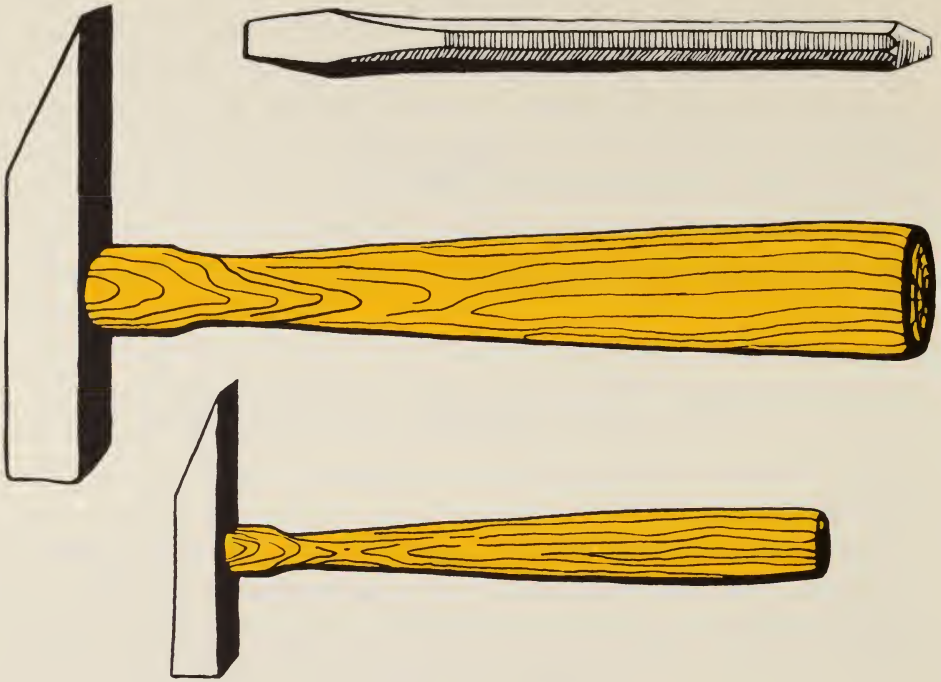
# DISCOVERING THE EARTH

## 16. The study of fossils

*Collecting*

Larger fossils, if present in the rock at all, are usually best seen on weathered surfaces because the slow, delicate action of rain or sea water will often pick out fossil detail more clearly than any hammer and chisel. However a hammer and chisel will be needed, for so often a fine fossil is found in the middle of a large slab of rock, and in order to collect it a great deal of chiseling will be necessary. It is well to take a good look round first, for one may often find better specimens which are worth spending time to extract. A GEOLOGICAL HAMMER usually has a square head and chisel pane – best set crosswise to the shaft – so that it can be used to split shale. Never use the chisel end of the hammer for cutting across or into the rock. It is best to keep this sharp for splitting only, and to carry an extra cold chisel, about nine inches long and half an inch across, which can be carefully directed so as not to damage the fossil by an accidental blow.

If you are collecting a great deal, it may be worth having two or three sizes of hammer for different purposes. A short, heavy, mason's hammer is easiest to use with a chisel, if a great deal of chiseling is to be done. Sometimes a hammer with a pick end, or even a heavy pick, can be useful for removing masses of soft rock. After a piece of rock with a fossil on it has been removed, it is often convenient to trim it with a small light hammer, or trimming hammer. By holding the specimen in one hand, and striking very fast sharp blows at any pro-



The standard geological collecting tools are illustrated above. The large hammer is for breaking off rock and the small hammer for trimming. The large hammer is used with the chisel. There are many kinds of geological hammer in use. They must have specially tempered steel with a square face.

truding corners of the rock to be removed, small flakes can be taken off the main specimen one by one.

With experience it soon becomes apparent that a gentle blow with a heavy hammer has a quite different effect from a sharp blow with a light one. In the first case, any existing cracks tend to grow – so that if the specimen is about to break up the heavy hammer will complete the general distintegration. By contrast, a sharp blow will tend to have a localized effect. The heavy impact is sometimes helpful when a fossil has almost been extracted and a general vibration of the whole rock allows it to jump out from its matrix.

But this assumes that the rock is strong enough to need a hammer. Many deposits – especially of the younger rocks – are not very hard, and if the fossil is stronger than its matrix, fossil collecting is easier.

In such cases a small pick, or even a strong knife, will cut away the sand or clay.

All too frequently, whether the rock is hard or soft, the fossil to be recovered is liable to break up and be difficult to carry away. The beginner often underestimates the difficulty of getting a fossil out complete, and then, as time presses, is tempted to smash away at the rock in a last desperate attempt to procure the specimen – which in the end is only too often destroyed. If fossils are large and difficult to extract, it is well to plan carefully at first which ones to collect, and only to begin to cut away the rock if there is enough time to complete the job and some means of carrying the specimen away. Sometimes special containers are needed. In the case of large reptiles, many packing cases and a great deal of help in transport are essential. When fossils of this sort are collected piece by piece to be reassembled later, it is important to make sketches and take photographs of the bones in position and also to number each fragment itself and on a sketch.

For small specimens which are liable to break up, a box and some cotton wool or tissue paper are best. Indeed, it is well to go equipped with a number of boxes of different sizes, and perhaps small glass tubes for the tiny specimens – several tubes packed in a box. Plenty of newspaper will also be needed for wrapping the larger specimens, to protect them from each other while they are being carried.

In special circumstances the fossil is so easily crumbled that it must be hardened or supported before it can be removed from the rock. A little PLASTER OF PARIS, mixed with water on the spot, and allowed to harden on the specimen just before removal, will make a firm cradle to support it when it has been separated from underneath. A wetted piece of tissue paper should first be laid on the specimen to prevent the hardened plaster from adhering to it.

In addition to the fossils which can be spotted with the naked eye, there are also MICROFOSSILS, and for these a magnifying lens is needed. In any case a pocket lens should be carried in the field. A good magnification is about ten or twelve times. A higher magnification gives a smaller field of view, and you have to get much closer to the specimen so that you may not have enough light. With too high

a magnification you may see the detail but not the whole fossil. In any case it is well to examine all fossil material under the lens, for unsuspected microfossils may be revealed – and then there is not much more to be done in the field than to collect a sample in a tube, or in a paper or cloth bag. Most microfossils are too small to be recognized in the field, even with a lens, so that sample collecting for later study is usually necessary.

*Labeling*

Perhaps the most important part of collecting is to label as fully and as soon as possible. It is tempting to rely on remembering what was collected where, but nothing so important should be trusted to

A folding lens which can be carried in the pocket, of magnification about x 10, is necessary equipment for every geologist. The picture shows its use – especially how the lens is held firmly near the eye, and the specimen is brought into focus.

memory, and the really important thing to record about a fossil is exactly where it was collected. There are so many details to be noted that it is a good plan to number the fossil, and write the number with all the details in a notebook. Some collectors prefer simply to wrap a slip of paper around the specimen, but it is preferable to write the numbers on adhesive tape with a ball-point pen and then stick them on the specimens. These numbers can be prepared in advance by sticking a strip of tape on a tin lid, writing the numbers, and then cutting them across with a sharp knife or razor blade. In this way the same number will not be used twice, or one missed out, as so easily happens if the labeling is all done in the field. The numbered tape can be peeled off the surface and applied directly to the specimen before wrapping it up and entering it in the notebook.

The notes should give the fullest information about the exact locality, and if the fossil is collected from the solid rock, a cliff or stream, distances or heights should also be included. If, as so often happens, a good fossil is found lying loose, this fact should be added, but the position is still worth recording, as the fossil has probably not moved far unless it is on a steep slope, and even then it is not likely to have traveled uphill. For the records nothing matters so much as locality. It is not usual to try to identify fossils in the field, but if you happen to know what kind of fossil it is then write it down. For instance, if you know it is a brachiopod, this is worth recording, as you may end up with a variety of rocks, minerals and fossils and this will help to avoid any confusion. In general, a pocket notebook with stiff covers and a pencil is best, so that it can easily be slipped out and away again while collecting. Rubber bands will keep the pages from fluttering in the wind and help to find the place quickly.

If all these details are carefully attended to, a very valuable collection can be made without at first knowing much about the fossils themselves. In a serious piece of work it may be many years before some of the fossils are identified, and they may then turn out to be of very great importance. If this happens, it is important to know the exact locality, so that it can be revisited and any later finds can be related to the positions of the earlier collection.

*Developing fossils*

It is a good rule when in the field not to expose more of the fossil than is necessary to bring it home, thus avoiding damage to the fossil through too hasty work or, perhaps, through ignorance. At home you can sit more comfortably at a table and with a good light "dig out" some of the detail with a small chisel, or needle mounted in a stick or chuck. The specimen can be rested on a block of rough wood or a small bag of sand or lead shot, so as to provide a soft base without damaging the fossil. It is also useful to have an anvil, or alternatively any large stone or block of cast-iron, as some hammering needs a hard rigid base.

Different methods will be used according to the kinds of fossil being developed. For those with a soft matrix, a needle and brush will be sufficient, though various dental implements are used from time to time, from the discarded toothbrush to the dentists' probe (which is of excellent steel) and even the dentist's drill. Other mechanical excavating tools have been devised, but they are not always better than a steady hand with a sharp chisel point. Never scrape along the surface of the newly exposed fossil, but rather press down on the matrix against the surface so that the matrix flakes off piece by piece.

Many fossils, however, are in a matrix which is too tough to be developed mechanically in this way. For these, various acids may be used – but it is not advisable to try this without chemical ware and a good fume cupboard. Grinding can be attempted, in order to find out the internal structure of a fossil from a series of sections, and if this is done each stage should be photographed or drawn. Then, after a great deal of painstaking work it may be possible to reconstruct some of the internal structures of the fossil. This should only be tried in the first case with fossils of which you have duplicates, for the original fossil is destroyed in the process.

Unconsolidated sands and silts which may contain microfossils have to be separated into their individual grains and spread out for searching and sorting. A stereo-binocular microscope is valuable for this, but a large low-power lens mounted above a well-lighted sheet of paper, or glass with paper beneath, will serve well. In this case small

A fossil sea urchin was collected in the field and is now being "developed" at home. The specimen is placed on a bag of sand or lead shot, and a pointed chisel is being used to chip away the rock from the fossil with small taps of the hammer.

fossils may be picked up with the moistened tip of a fine-pointed brush. If they are white, a black background is best. They can then be separated from the sand grains, and sorted into groups of different kinds for mounting on special slides or storing in small sample tubes.

Here again a great deal can be done by patient and systematic work, without knowing much about what the fossils themselves are. This will all come at a later stage and cannot be done without first collecting, sorting and storing.

*Storing specimens*

Large institutions, as well as private individuals, find a perennial difficulty in the problem of storing a growing collection. It is pleasant to be able to display material as in a museum, but this is often beyond the immediate resources of an amateur. From a scientific point of view display is not so important if the material can be sorted and easily got

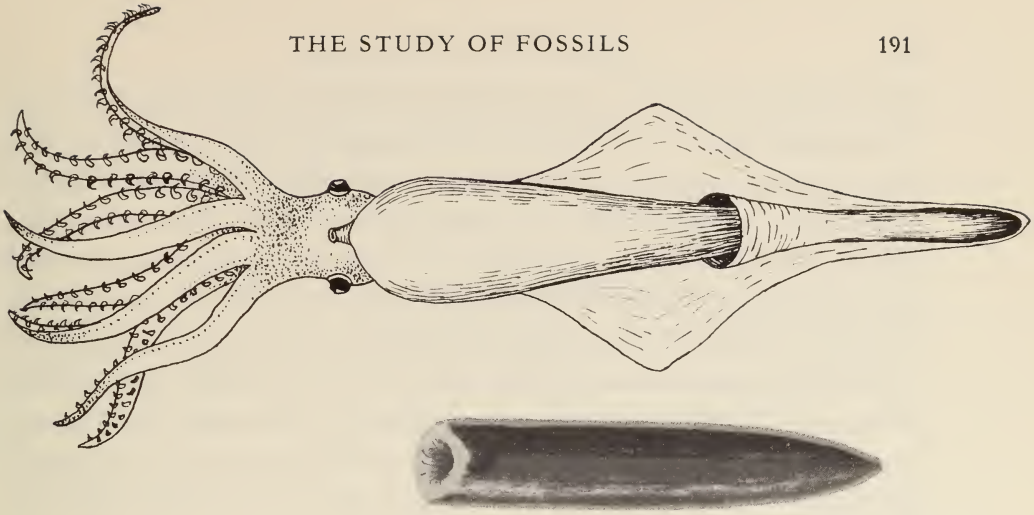
at for comparison. A series of boxes to hold specimens from different localities, and labeled on the outside, is a good beginning. Then, as the material is developed and sorted, it is more satisfactory to lay the specimens out individually in small cardboard trays, which, in turn, are grouped in larger wooden trays. The latter should be labeled on the outside and piled up, or placed in a rack, or better still in a specimen cabinet. The small individual trays or tubes are important, both to protect the specimens from rolling against each other and to keep them in position inside the larger trays.

At the earliest opportunity labels should be made out from the field notebook to go with the specimens, preferably to be stuck on them, or to go in the tray. It is so easy for notebooks to become separated from specimens, and perhaps scores of years hence the specimens may still be valuable if the exact locality is known, Needless to say, a large collection may take up a great deal of space, but provided the specimens are well labeled in indelible ink, space may be saved by storing whole collections wrapped up in paper in boxes, if they are not being used for some time.

*Identifying fossils*

Identifying or describing the specimens which have been collected is a most difficult task, and it is a kind of work which is never finished, for new material is constantly being found and ideas are continually changing as to the best way of grouping fossils into species, GENERA, FAMILIES, ORDERS, CLASSES, and PHYLA. Naturally, the ideal method is one in which the members of a family are related to each other in a real way, and not simply because they look rather similar – and this is what causes the difficulty. The identification of fossils is not just an end in itself, but also a means to understanding the complex evolutionary tree. On the one hand names are needed immediately for purposes of reference, and on the other hand the names will tend to be revised as more knowledge accumulates about the NATURAL CLASSIFICATION of the fossils. And the knowledge which accumulates depends on continued collecting all over the world.

Fossils are commonly given two names, usually in Latin form. The



The lower illustration is a belemnite, a common Mesozoic fossil. It consists of a solid mass of calcite, just about this size. It was for long uncertain what organism it belonged to, but eventually it was shown to be a small hard part of an animal reconstructed above, and related to a cuttlefish and octopus in the pelecypod class of molluscs.

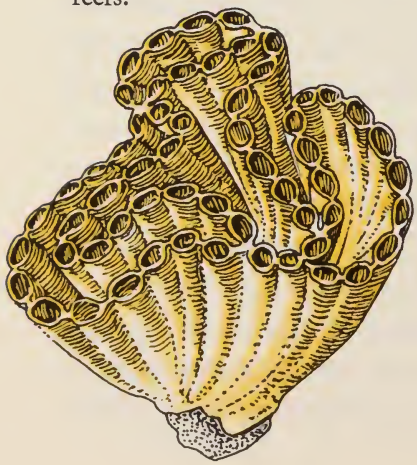
first, or GENERIC NAME may refer to several rather similar kinds while the second, or TRIVIAL NAME refers to the particular species. To be complete this should be followed by the name of the person who first described the species and gave it its name. The SPECIFIC NAME is thus the generic name plus the trivial name, plus, possibly, the author's (describer's) name. If it is later shown that a species placed in one genus could be better arranged in some other way, the generic name of the species may be changed, but if possible the trivial name is retained. This explains why so often various names are given to fossils that are obviously the same, and why in different books and museums you may see the same fossils with quite different generic names but usually with the same trivial name.

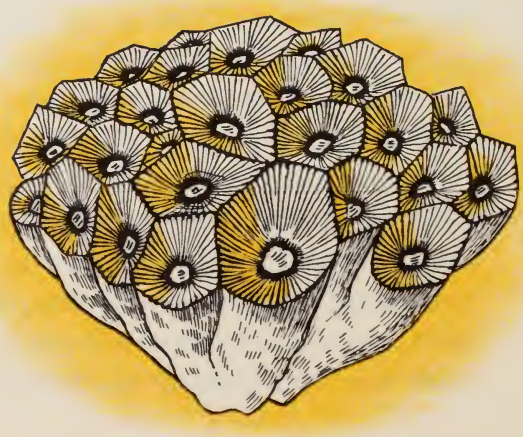
What has just been written shows that the identification of fossils is really impossible without thorough preparatory study. This usually involves specialization by one person who has tried to find out all about a small group of fossils, and can thus get to know the group well enough to tell whether any newly-discovered fossil fits into a known species or needs a new specific name – or possibly even upsets the scheme which was satisfactory until the new fossil was found. This

kind of study is carried out by many specialists in institutions and universities and also by a number of amateurs. It cannot, however, be done without access to a good library containing the published work of previous authors who have described and illustrated the fossils known to them. Access must also be had to good museum material for comparison (though museums all over the world may be written to, if such a study is being made, for specimens which may be helpful). It is the main purpose of such museums to store this kind of material, particularly fossils which have been described and possibly used in the first place for naming a new species. This material may then be sent to different parts of the world for comparison, as the fossil itself will show more than the published description of it.

A great deal more could be written about this process, but it should already be clear that a beginner can seldom get very far without a great deal of personal help and study. It should also be clear, however, that the fossils collected by anyone may, if they are properly located, be of value in this study – provided they eventually find their way to museums where they will be looked for. Today there are few individuals with large private collections. Most geologists begin with a small private collection and, sooner or later, begin to specialize and possibly

Two examples of fossil corals typical of the Silurian and Devonian periods. They belong to different groups, but each developed the colonial way of living which later was to emerge as a dominant reef-building and rock-forming process. However, many corals were solitary, lived on the sea floor and had nothing to do with reefs.





to work with some institution which may take on the expense of storage, and provide facilities for the preparation of material, as well as a good library for reference.

But this does not mean that you cannot do anything without the help of such an organization. You may be able to collect as well as any professional, and you can get an approximate identification for your fossils by comparing them with fossils in any good museum or in some of the larger illustrated books. The trouble in either case is that there are so many thousands of fossil species that the answer may not be found in a small museum or a small book.

Perhaps the best single book for this purpose is the rather expensive *Index Fossils of North America*, which gives pictures of thousands of common fossils and arranges them systematically. If you have to use this from a library it may be helpful to get a smaller book for yourself which, although it cannot give pictures of very many fossils, can nevertheless give you an idea of the main groups into which fossils are placed. This is all that it is really necessary to know. If you can identify a fossil, not as a species but simply as one of a class, order, or family, you will be doing as much as most professional geologists who are not actually specialists. Having got so far you can describe your collection in a way that will be useful to other people, and it will be clear whether the fossils may be of interest to a particular expert.

In this book it is impossible even to begin to go into the principles on which the animal and plant kingdoms are classified. You may have already had some help from the study of biology, but the examples of living things that are usually chosen are not the most suitable for the study of fossils, which so often show only the hard parts. However, the same principles and classification are used, for it is all one science. Charts Four and Five show a broad classification of the plant and animal kingdoms as used in the study of fossils, and some of the examples given there, as well as the various examples of fossils illustrated in this book, will serve to show the principal characteristics of the main groups of fossils.

As with any detailed study, it is difficult to get very far without help from a friend who has had some experience. But geologists are not

rare and are usually only too glad to help. The decision as to what course of action is best depends enormously on the local circumstances in each individual case, and it is therefore pointless to offer further advice that might apply to one situation, but which would be useless for any other.

The pioneers had no one to help them and, working from first principles, they collected material and arranged it as they thought best. You, too, may be in a position to do this. The important thing is to collect carefully and label carefully with the localities. The reward is to obtain a glimpse of the procession of life through the ages and possibly to discover some fragment of the record not yet known. It is one of the few fields in which the keen amateur can contribute directly to the patterns of scientific discovery, as can be seen from this extract.

"In May 1957, a Leicester schoolboy, Roger Mason, reported to the writer the discovery of a possible fossil plant in the Pre-Cambrian rocks of Charnwood Forest, Leicestershire. The report was investigated, and not only was the existence of the fossil confirmed, but several more of two distinct kinds were found at the same locality. Although their nature remains uncertain it is thought that they are worth recording. Several other localities at similar horizons in the Charnwood succession have been searched in vain." (From "Pre-Cambrian Fossils from Charnwood Forest", by Trevor D. Ford. *Proceedings of the Yorkshire Geological Society*, Volume 31, Part 3, p. 211, 1958.)

It may be added that most geologists in England had, at some time or other, visited the quarry where the finds were made. Many would not have searched for fossils, in the knowledge that Pre-cambrian rocks are (nearly) un-fossiliferous.

The animal kingdom is divided above into broad divisions of phyla and classes. Only those groups important in the fossil record are given. Individual fossils are grouped into species, then into genera, families and orders, many of which constitute the classes shown here. The few examples chosen are selected to illustrate the meaning of the technical names. A zoological or paleontological text-book will be necessary for futher information on this classification.

# THE ANIMAL KINGDOM

## CHART 5

| Phylum or Sub-phylum | Technical and Common Name of some classes | Living examples | Fossil examples |
|---|---|---|---|
| CHORDATA (VERTEBRATA) | Mammalia *Mammals*<br>Aves *Birds*<br>Reptilia *Reptiles*<br>Amphibia *Amphibians*<br>(Various) *Fish* | *Elephant, horse*<br>*Eagle, penguin*<br>*Snakes, lizards*<br>*Frogs, newts*<br>*Herring, coelocanth* | *Megatherium, Glyptodon*<br>*Archaeopteryx*<br>*Ichthyosaurus, Triceratops*<br>*Branchiosaurus*<br>*Dipterus* |
| | *Graptolites* | *Extinct* | *Monograptus* |
| ECHINODERMA | Echinoidea *Sea urchins*<br>Asteroidea *Star fish*<br>Crinoidea *Sea lilies* | *Heart urchins*<br>*Brittle stars* | *Cidaris, Micraster*<br>*Apiocrinus* |
| ARTHROPODA | Myriapoda<br>Insecta<br>Arachnida<br>Merostomata<br>Trilobita<br>Crustacea | *Centipedes and millipedes*<br>*Butterflies, beetles, flies*<br>*Spiders*<br>*King crabs*<br>*Extinct*<br>*Crabs, lobsters* | *(known)*<br>*(known)*<br>*(known)*<br>*Eurypterids*<br>*Trilobites e.g. Olenellus*<br>*Ostracods* |
| ANNELIDA | | *This is only one of many groups of living "worms"* | *Fossil worm tubes and trails may belong to this phylum* |
| MOLLUSCA | Cephalopoda<br>Pelecypoda<br>Gastropoda | *Pearly nautilus, cuttlefishes, squids*<br>*Mussels, oysters*<br>*Snails, whelks, limpets* | *Ammonites, belemnites*<br>*Pecten, Gryphaea*<br>*Euomphalus* |
| BRACHIOPODA | | *Lingula* | *Lingula*<br>*Productus, Rhynchonella*<br>*Terebratula* |
| BRYOZOA | | | *Fenestella* |
| COELENTERATA | Anthozoa<br>Stromatoporoidea<br>Hydrozoa | *Reef building corals*<br>*Extinct*<br>*Jellyfish, Hydra, Obelia* | *Solitary and reef corals*<br>*Reef-building coral-like organisms*<br>*Soft bodies, preserved as impressions* |
| PORIFERA | *Sponges* | *Bath sponges* | *Archaeocyathus* |
| PROTOZOA | Foraminifera *"Forams"*<br>Radiolaria | *Globigerina* | *Fusulina, Nummulites* |

The Canadian Shield; ancient rocks including many Precambrian orogenic belts.

Interior Lowlands: Paleozoic and later sediments gently warped into domes and basins above shield beneath.

Coastal plains: late Mesozoic and Tertiary rocks dip away beneath the sea.

Tertiary and Quaternary volcanic rocks including active volcanic areas.

Folded and faulted sedimentary rocks

Folded and metamorphosed sedimentary and volcanic rocks

Granite masses within fold structures

} of post-Cambrian orogenic belts.

Sea and lakes

# 17. The study of minerals

The study of minerals is in some ways rather easier than the study of fossils, for the number of kinds of minerals that is likely to be found is small. But though a private collection which contains only a few examples of each mineral species will not be a large one, it may nevertheless be a very beautiful one. The total number of different kinds of minerals is comparatively small, partly because the same minerals have been formed in similar conditions at different geological ages. It is thus possible to get to know most of the common ones, and it is unlikely that you will discover any new minerals. On the other hand, you may easily be the first to find a known mineral in a new situation and so add to knowledge in this way.

*Collecting*

In collecting minerals the principles are in many respects the same as those applied to fossils. That is to say, you should go well equipped with packing paper, and small boxes and tubes for delicate or small specimens. Hammers and chisels will be needed, but in the case of minerals it is not often that a single particularly fine crystal has to be detached from the rock – it is more likely that if the mineral is present it will be abundant enough for one or more pieces to be hammered off the rock. As with fossils it is important to label carefully – preferably by numbering the specimens and recording details in a pocket notebook or on a map – for the one piece of information that cannot be found out later, if it is not recorded, is the locality.

This is a diagrammatic map of the main geological features of North America simplified after P. B. King's *The Evolution of North America* (Princeton). The best small scale map on which the systems are shown is published on two large sheets by The Geological Society of America at a scale of 1/5,000,000.

*Simple tests and observations*

There are various simple observations which may be made later at home but it is just as well to get into the habit of attempting an identification in the field. Indeed, in many cases there will be no particular point in collecting a specimen, as long as the mineral can be identified and recorded. Many geologists only collect samples of the minerals they want to study in the laboratory and for the rest simply record them on the spot in the field.

One of the most obvious characteristics of a mineral is its color and this is the first thing to be recorded – though in fact it may often be misleading. Most minerals are colorless and often appear white, but many of them may be colored very beautifully by minute traces of other substances. Thus FLUORITE is colorless when pure but is normally tinted by impurities, giving wonderful shades of blue, purple, green and yellow. Quartz is commonly white, but with traces of carbon in it a "smoky" variety is produced, and with manganese it may become the gemstone AMETHYST. Often the cause of the tinting is not clear, but whatever it is it gives scope for enlarging a collection by adding the different colored varieties of each mineral. Self-colored minerals, on the other hand, are usually quite distinctive, such as the brilliant red of some mercury ores, or the green of malachite.

Many minerals show different colors in different conditions. The color of the crushed mineral or powder may be different from its color in large crystals, and a useful test is to crush a little of it, or simply to scratch a knife across the surface. If the knife is harder than the mineral, a small trail of powder is left, which can be seen through a lens. In the laboratory a piece of unglazed white pottery or porcelain is sometimes kept, so that the mineral can be scratched across it, the resulting STREAK showing the color of the powder.

Some minerals show a distinctive luster. As opposed to color, luster refers to a quality of the mineral's appearance – such as pearly or metallic. Other examples are the slightly resinous luster of sphalerite or the glassy luster of quartz.

Finally, a very important difference may be seen when a mineral is looked at in a very thin slice. When light is passed through the slice

colorless minerals may become translucent or even transparent, and those minerals which appear dark or black in a small lump may become almost colorless or vividly colored. A few minerals – mostly those with metallic luster – will not allow any light to pass through them, even in very thin slices, and these minerals are known as OPAQUE.

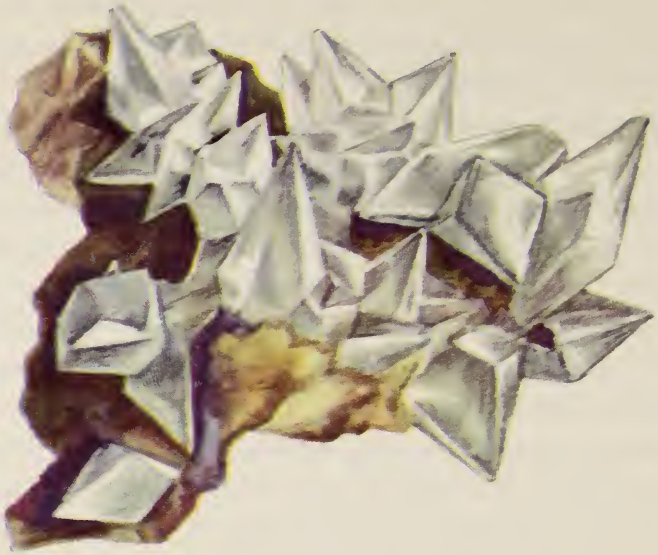
Thus we may see color both by light reflected from the surface of a mineral, and by light transmitted through it. A few minerals have an iridescent appearance, with a variety of colors changing in different positions. This is due to some reflection and interference of light inside the crystal. A good example of this is LABRADORITE FELDSPAR – though this is not always iridescent.

There are other mineral properties which may be tested mechanically and are useful in the field. HARDNESS is, perhaps, the simplest to interpret. All minerals have a specific range of hardness which can be tested quite easily, according to MOH'S SCALE, thus:

10. Diamond (scratches all other minerals)
9. CORUNDUM (scratches all minerals except 10)
8. TOPAZ (scratches all minerals except 9 and 10, and so on)
7. Quartz (scratches glass and most steel)
6. Feldspar (just scratched by steel)
5. APATITE (as window glass, just scratched by steel)
4. Fluorite (easily scratched by steel)
3. Calcite (scratched by bronze coin)
2. Gypsum or rock salt (scratched by finger nail)
1. TALC (feels greasy and marks paper)

One can do much in the field with penknife and finger-nail, bearing in mind that these vary much in hardness themselves, and that, unlike scratching, breaking is not a test of hardness but of strength. You must also be careful to see what has been scratched by what. Using a lens you may find that there is a little trail of steel over the surface of the mineral, and therefore the mineral is harder than the knife and not the other way round.

Another clue to the identity of a mineral is the way in which it breaks. With a good crystal form it may be clear that the mineral



Dog-tooth spar, shown above, is one of the many forms of the mineral calcite. Another form, with blunt-ended crystals, is nail-head spar. On breaking the crystals open the different forms are indistinguishable. All break into parallel-sided rhombohedra along three good cleavage directions, which are not parallel to the common crystal faces.

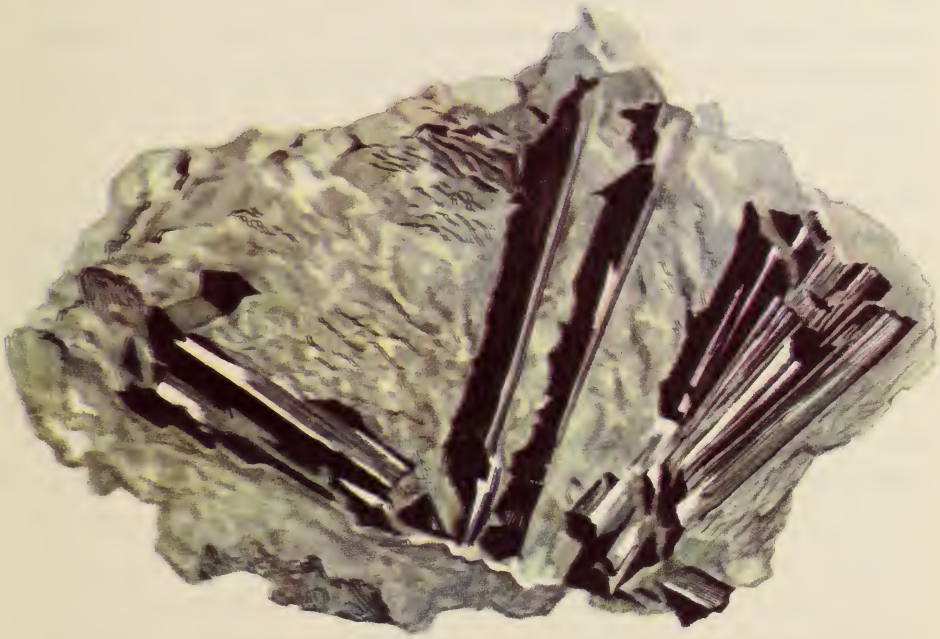
"cleaves" easily in definite directions in relation to this. Some minerals, such as mica, may be distinguished by their single, perfect cleavage. Others, such as calcite, have three equally good cleavages which allow the mineral to break up into small rhombohedra. Quartz has no cleavage but breaks, like glass, with a conchoidal fracture. Fluorite, which crystallizes in a cube, has four cleavages which together produce a perfect octohedron, each cleavage cutting off a corner of the original crystal cube.

One of the most important characteristics of a mineral is its crystalline form, and most of its other properties depend on this – but the study of CRYSTALLOGRAPHY is beyond the scope of this chapter, except to say that the regular form which some crystals show is merely the outward effect of crystals being built up from minute units of distinct atomic pattern and definite shape. The properties of the mineral depend on the kind of units of which it is built.

Ideally, then, minerals should have an obvious crystallographic

form with regular faces developed, but although most minerals have not had an opportunity to grow crystal faces, they still have the same internal structure and therefore the same crystallographic properties. All rocks are made up of mineral crystals, though few show any outward crystalline form. There are various ways of discovering the internal crystalline form – one of which uses the POLARIZING MICROSCOPE, and will be considered briefly in the next chapter under the study of rocks. Actually the study of rocks really depends very largely on a study of the minerals from which they are made.

There are several other physical properties which can be easily observed. The density or specific gravity of a mineral is the weight of a given volume. This is normally expressed in grams per cubic centimeter. One cubic centimeter of pure water at standard temperature and pressure is defined to weigh just one gram. The density, or SPECIFIC GRAVITY, of a material expresses its weight in relation to the



Tourmaline is a complex silicate which commonly grows in rocks altered by permeating gases, near a granite intrusion. The black striated crystals, like calcite, have threefold (trigonal) symmetry.

same volume of water. Metallic ores like galena are as dense as 7·5, or hematite 5·0, but most of the common rocks and the commonest minerals which make them up are between 2·5 and 3·5. With experience, after getting used to handling specimens of these densities, it is possible to tell whether a specimen is near the lower or upper limit. For example, since most white minerals fall within the 2·5 to 3·5 range, a specimen of BARITE (density 4·5) can be detected immediately by its density; for this reason it is commonly known as "heavy spar."

Magnetite is easily distinguished because it is magnetic and readily affects a compass needle held close to it. Some other minerals are slightly magnetic, but magnetite is by far the most conspicuous; it has long been known as the lodestone, and was used as a natural compass.

Most minerals can be identified by using physical methods such as those mentioned above – especially the optical methods which, with the help of the polarizing microscope and special training, are very quick, clean and effective. The way the internal crystal structure is made up from the repetition of a particular pattern of atomic lattice is found out by a still more elaborate method of investigation, using X-rays. But whichever mineral is being described, an ordinary chemical analysis is made at some stage.

*The chemistry of minerals*

A chemical analysis may be a long and difficult process but there is one simple test which anyone can apply. Dilute hydrochloric acid, when added to most CARBONATES, will bubble or effervesce. This is certainly so in the case of calcium carbonate, and, since calcite is not only the commonest mineral of this composition but also one of the most abundant minerals in nature, this is a very good test. Indeed, it may be useful to carry a small acid bottle in the field. This should be a tough bottle with a screw top and a small attached pipette or eye-dropper, such as is supplied with medical preparations for dispensing single drops. At the drug store you should ask for hydrochloric acid one-in-ten, and this can be carried safely in your pocket in the field and used to test rocks for calcite. Any limestone, for instance, will "fizz". Be careful not to carry the acid bottle, which might leak, next

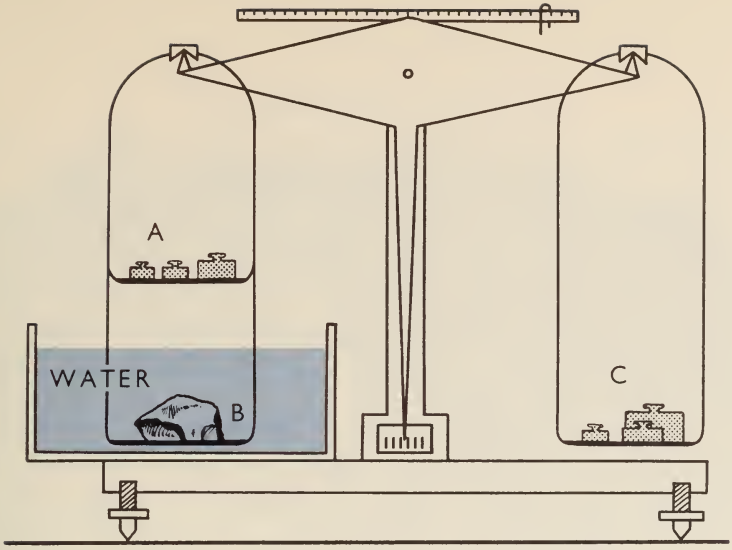



Diagram of weighing a rock or mineral rapidly to find the density. The specimen is first placed on pan A and its weight is C. It is then placed in water on pan B and weights are placed on A to equal the buoyancy of the water. The density is then C ÷ A. Different answers depend partly on how much air is left in the pores of the specimen when submerged.

to a camera, penknife or other valuable instrument.

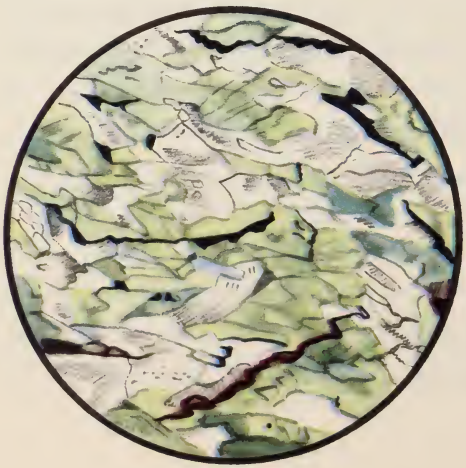
There are other simple chemical tests which can be applied, but to anyone who has studied chemistry it will be clear that some minerals can be tested easily and others – especially the very important group of SILICATES – only with great difficulty. The minerals listed in Chart Six are classified chemically, according to native or uncombined elements, into sulphides, HALIDES, oxides, sulphates, carbonates, and silicates. The last two groups are the most important groups of rock-forming minerals. The carbonates are the essential constituents of limestones and DOLOMITES, and the silicates are abundant in all igneous and metamorphic rocks, as well as clays. The only other really important rock-forming mineral not included in these groups is quartz, and that may be regarded either as an oxide (chemically) or as a silicate (crystallographically).

*The common minerals*

Chart Six lists some of the common or more important minerals. The silicate group is by far the richest in variety as well as in geological importance. Each of the names listed refers to a group or family of

Section of hand specimen of diorite to show orbicular structure. Most igneous rocks show an even granular appearance, due to random crystallization of the magma. Occasionally, however, as in the illustration, the minerals groups concentrically in alternating layers of light and dark minerals.

minerals. There are many kinds of feldspar (ORTHOCLASE, MICROCLINE, ALBITE and ANORTHITE PLAGIOCLASES), and there are other micas besides the MUSCOVITE, or common white mica, and BIOTITE, or dark mica. The AMPHIBOLE family contains minerals such as hornblende – important in granites, and gneisses – and ASBESTOS, which is a mineral with very long fibrous crystals, and good cleavages running

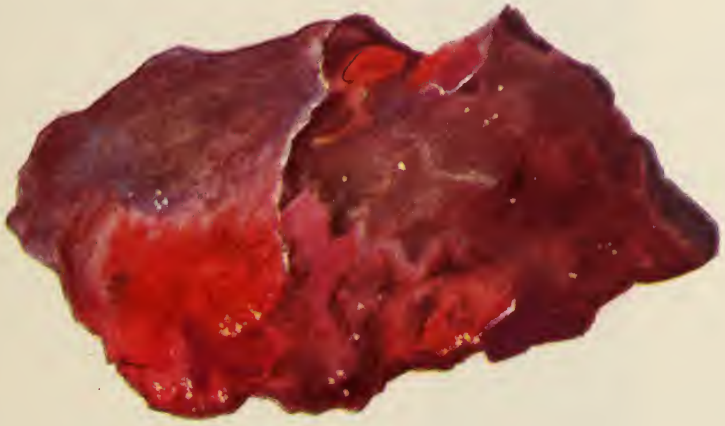


Thin section of hornblende schist, as seen through the microscope. The section is about one thousandth of an inch thick. Solid crystals of hornblende are black and opaque, but thin sections pass light and show a brilliant and distinctive variation of colors, mainly green. Hornblende schist is a typical metamorphic rock.

parallel to the long fibers without crossing them, which makes it a kind of natural rock wool. AUGITE is one of the best known PYROXENES and it is one of the most important constituents of the basic igneous rocks. Each family has many members, some rare and some common, and the species, or members, show considerable variety among themselves.

Reference must be made to a text book of mineralogy for more details about the common minerals. Many books on physical geology contain a chapter on the common rock-forming minerals and some of their properties, but a book on mineralogy will give fuller details of the different species, how to identify them, and how they occur.

This bright red mineral is cinnabar, a mercury sulphide. It is usually impure, with inconspicuous crystals. Cinnabar is commonly associated with volcanic activity. It is the most important mercury ore, and the mineral is the base of vermilion pigment.



# MINERALS

## CHART 6

| Chemical Classification | Mineral Name | Chemical Composition | Remarks |
|---|---|---|---|
| ELEMENTS | Sulphur | S | Mined in volcanic regions |
| | Diamond } | C | Different crystalline forms of the same element |
| | Graphite } | | |
| | Native Gold | Au | |
| | Native Silver | Ag | |
| HALIDES | Halite | NaCl | Rock salt |
| | Fluorite | $CaF_2$ | |
| SULPHIDES | Galena | PbS | Main lead ore |
| | Sphalerite | ZnS | Main zinc ore |
| | Chalcopyrite | $CuFeS_2$ | Main copper ore |
| | Pyrite | $FeS_2$ | "Fools' gold"; sometimes used as source of sulphur |
| OXIDES | Quartz | $SiO_2$ | In granites, gneisses and sandstones |
| | Hematite | $Fe_2O_3$ | Red iron ore |
| | Magnetite | $Fe_3O_4$ | Lodestone |
| | Limonite | $Fe_2O_3nH_2O$ | Brown iron ore |
| | Bauxite | $Al_2O_32H_2O$ | Important source of aluminium |
| SULPHATES | Barite | $BaSO_4$ | Heavy spar |
| | Anhydrite | $(CaSO_4)_2H_2O$ | Formed from sea water at higher temperatures than gypsum |
| | Gypsum | $CaSO_42H_2O$ | Used for plaster of paris cement |
| CARBONATES | Calcite | $CaCO_3$ | Most important constituent of limestone |
| | Dolomite | $(CaMg)CO_3$ | |
| | Siderite | $FeCO_3$ | |
| SILICATES | Feldspars | Alumino silicates of potassium, sodium, calcium etc. | Common in all igneous rocks |
| | Micas — Muscovite | | |
| | Micas — Biotite | | Common in granites and silts |
| | Amphiboles<br>Pyroxenes<br>Olivines | Ferromagnesian silicates | Dark minerals, common in darker and more basic igneous rocks |
| | Chlorites, Serpentines | | Common minerals formed by weathering of igneous minerals |
| | Clay minerals | Aluminous silicates | |
| | Garnet<br>Kyanite | | Common metamorphic minerals |
| | Tourmaline | | |

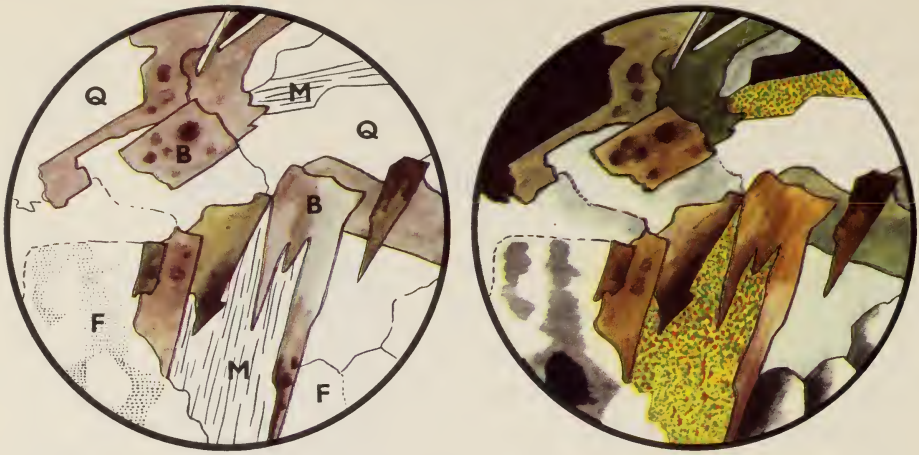
# 18. The study of rocks

Rocks, unlike fossils and minerals, are unlimited in their variety, for their various mineral ingredients may be mixed in many different proportions, depending on circumstances. Thus rocks do not belong to natural species, so the problem of naming them is to be approached in a different way. Within certain limits they vary continuously; when different kinds are to be specified, certain characteristics or ranges of properties are agreed, and these are then used to define, as it were, a series of pigeon-holes or boxes. Any individual rock may fall in the middle of a box or right on the edge of it. The classification is arranged so that as few rocks as possible fall on the edge, but this cannot always be avoided.

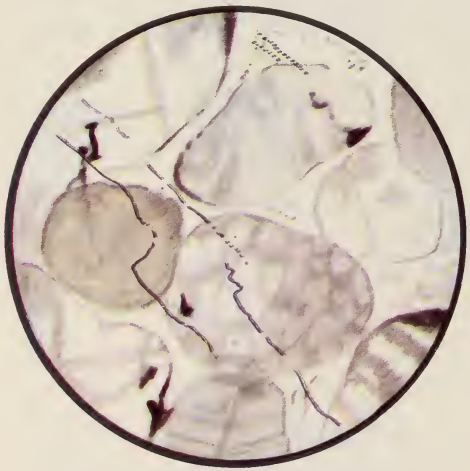
Rocks are composite and cannot be fully understood without a knowledge of both the minerals of which they are compounded and the fossils which may be found in them. It is necessary, too, to know how far particular rock-formations extend and what their boundaries are like – in other words, their structure and relationships. When all these are fully understood the rocks, taken together, give us the story of the earth, so they are indeed a rewarding study. This chapter, however, will first concentrate on the different kinds of rocks and ignore their different ages. Age is deduced from fossil and structural evidence rather than from the rock itself, and on geological maps is usually distinguished by colors.

Petrology, or the study of rocks in themselves, has two aspects. One describes the specimen of rock (PETROGRAPHY) and the other

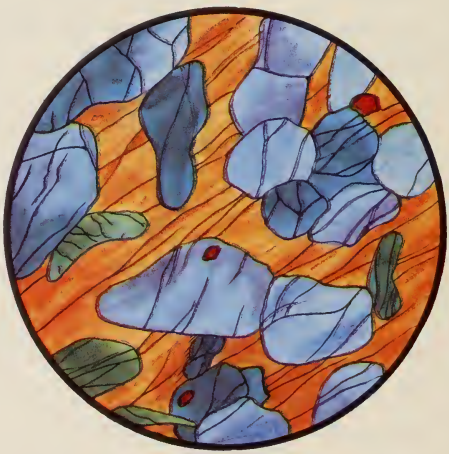
More than a thousand mineral species are known, but there are relatively few common minerals, and some of these are listed in this chart. To describe a mineral adequately it is necessary to state its exact crystal form, physical properties and chemical composition. Some of these are illustrated in the glossary.




Thin section of muscovite-biotite granite (x 20), a coarse-grained acid rock. Left: as seen in ordinary light, and right: with the polarizing attachments which add distinctive interference colors to the means of identifying the minerals. These are Quartz: Q, Feldspar: F, Muscovite: M, and Biotite: B.



Thin slice of quartzite seen through a microscope (x 40), and viewed in ordinary light. The rounded grains are sand grains of quartz and the matrix between is also quartz, so the rock is solid quartz, but the original structure can be seen in the section and in the hand specimen.



Thin section of augite peridotite (x 16). This is an igneous rock of ultrabasic composition, and belongs to the peridotite family. Peridot is an old name for olivine, which is seen as the granular crystals in a large augite crystal. In ordinary light the slice would be almost colorless. The bright interference colors illustrated are seen when the polarizing attachments are used with the petrological microscope.

interprets the origin of the material described (PETROGENESIS). The first step is description, and this must include both the composition of the rock and its texture. Most books assume that you know at the outset whether the rock is igneous, sedimentary, or metamorphic, even before describing it, and Charts Seven, Eight and Nine are arranged on this basis. But it is not always obvious at first (although the composition and texture will usually give a very strong indication), especially in the case of the very fine-grained rocks whose nature is difficult to discern.

The variety of rocks is so great that the most useful thing to do in this short chapter is to emphasize some of the main points about collecting them and studying them at home.

*Collecting rocks*

At first it is worth while to collect an example of each sort of rock, wherever it is found. Later on, rocks will be collected for some special reason – as clues to some other problem rather than as ends in themselves. But whatever the reason for collecting, the same precautions should be taken about careful numbering, recording, and labeling, as already explained in connection with fossils.

The specimen itself should be collected with care. Each specimen should show at least some unweathered rock, so the geological hammer is necessary. It may be a good idea, however, to collect a specimen with one surface showing how the rock weathers. First take some trouble to select the rock to be collected. You should look for the best place for sampling what you want, and also for a good place to break off a large piece – which is not always easy. If the rocks are hard, you need a hammer more than one pound in weight, or even as heavy as three pounds for the toughest rocks. A good general-purpose hammer would weigh one and a half pounds, and should have a square face and chisel pane. Always break the rock with the face of the hammer and reserve the chisel end for splitting rock. With experience most of the work can be done with a hammer alone. It is well initially to strike off a piece of rock larger than is actually needed, and then to hold this in one hand and knock off the edges, bringing it

# IGNEOUS ROCKS

## CHART 7

| Composition \ Texture | Coarse and medium* grained examples | Fine grained and glassy† examples | |
|---|---|---|---|
| **"ACID"** — *High silica content gives an igneous rock with more than 10% quartz. Most of the rock is feldspar* | **GRANITE** and Microgranite* — *Muscovite-granite, biotite-granite, and hornblende-granite, contain these minerals in addition* | **RHYOLITE** | *A fine-grained light coloured rock may be called a felsite* |
| *APPROX. 65% SILICA* | | | |
| **"INTERMEDIATE"** — *These rocks may be distinguished under the microscope by their characteristic feldspars and little or no quartz* — *Alkali feldspars* | **SYENITE** and Microsyenite* — *Mainly potash and soda feldspar, and some dark minerals* | **TRACHYTE** | Obsidian† — *A black glassy rock* |
| *Calc-alkali feldspars* | **DIORITE** and Microdiorite* — *Commonly soda-lime feldspar and hornblende* | **ANDESITE** | *A fine-grained dark coloured rock may be called a greenstone* |
| *APPROX. 55% SILICA* | | | |
| **"BASIC"** — *Essentially with a lime feldspar and a large proportion of dark ferro-magnesian mineral* | **GABBRO** and Dolerite* — *Commonly lime feldspar and augite* | **BASALT** | |
| *APPROX. 45% SILICA* | | | |
| **"ULTRA-BASIC"** — *No quartz. Usually much ferro-magnesian mineral* | **PERIDOTITE** — *Commonly lime feldspar and olivine* | *Fine-grained ultrabasic rocks are not known* | |

down to the required size. This second stage is best done with a trimming hammer, but if necessary it can all be done with one hammer of medium weight. When striking, take care that nobody (yourself included) is hit by small flying chips of rock, or even particles of steel from the hammer itself. Hard rocks are always liable to splinter and eyes are vulnerable. Spectacles are an advantage, but it is well to get into the habit of placing yourself in such a position that your face is behind the swing of the hammer. With very tough rocks, if you are not wearing spectacles, it is wise to blink at the moment of impact – not too early but just in time to stop any powder getting into your eyes.

A specimen need sometimes be only about the size of a matchbox, but museum specimens are commonly $5 \times 4 \times 1$ or 2 inches. Something between these two extremes should be aimed at so that the specimens tend to be the same size, and therefore more convenient for storing. The finished specimen should not show any hammer marks. This can be achieved if the specimen is held in the hand while trimming and reduced to the required size by striking off small chips round the edge, hitting as fast as the hammer can be swung and only just touching the specimen. The square top edge of the hammer will make it possible to shape a convenient rectangular block. Most people do not take sufficient trouble when trimming their specimens, and thus lose an opportunity of learning more about the rock in the field where there is plenty of it. Resist the temptation to knock it into shape at home (and remember that precisely the opposite advice was given for fossil-collecting). The difference is that any fossil may prove to be unique and should not be subjected to the risk of damage. A rock, on the other hand, is only a small sample of a great supply, and it is as well to try to get the best sample possible while there is still plenty of suitable material at hand.

All rocks may be classified according to composition and texture, and this is easiest to use for the igneous rocks since magmas of different chemical composition will solidify giving their characteristic mineral composition and any of a number of textures according to the circumstances of cooling. Hence the different rock types indicated in capitals.

Collecting rocks in the field is useful practice whether or not they are taken home, for by preparing the specimens you see more of the rock, and by carrying them along you can compare them with the next rock and get a better idea of the variation. Study them as much as possible in the field, for what you find may lead to a closer examination of neighboring rocks. Use a pocket lens frequently to find out what you can, and then record what you have seen in a notebook. Writing down your observations is one of the best ways of ensuring that you observe closely, which is important whether or not you are taking a specimen back.

Notice whether the rocks are in "in situ" – that is to say, in position – or are detached boulders. Observe also whether the specimen you have examined is typical of the whole rock, or whether it is, for example, a bit of pebble incorporated in a CONGLOMERATE.

*The study of rocks under the microscope*

One of the principal reasons for collecting rock specimens is to enable a closer examination to be made of them, and in most geological laboratories this is done by using a petrological microscope to study slides made from the rock. While such an instrument may be beyond your means at first, it is worth knowing about. Also it is possible to make your own slides without expensive equipment.

As with most studies, by far the best plan is to try to find someone who can show you how to do things, or better still show you some slides under the microscope, for they are often of quite surprising beauty. It would take too long here to describe in detail how a microscope is used for identifying minerals, for it is a highly specialized study: suffice it to say that it is usually the best and quickest method of identifying both rocks and minerals. With only a pocket lens you can see more in a thin rock slide than in the rock specimen itself.

Sedimentary rocks show a much greater variety of both composition and texture than igneous rocks. In this chart the chemical compositions are used as a basis of classification, and examples of common rocks are given, each with its distinctive texture. For the further study of rocks a text-book of petrology will be useful.

# SEDIMENTARY ROCKS

CHART 8

| Composition | | Common Rocks | Remarks |
|---|---|---|---|
| MIXED and IGNEOUS | | Agglomerates (*coarse*)<br>Ashes and tuffs (*fine*) | *Pyroclastic, i.e. formed from volcanic explosions* |
| | | Loess | *Wind-borne dust deposited near deserts* |
| | | Arkoses and greywackes | *Medium and fine-grained sediments with many undecomposed igneous minerals* |
| | | Tills and tillites | *Modern and ancient boulder clays deposited by ice* |
| | | Gravels and conglomerates | *Rocks formed of pebbles* |
| SILICEOUS | | Sand and sandstone<br>Silt and siltstone | *Mostly quartz grains*<br>*Quartz, mica, and other grains* |
| ALUMINOUS | | Clay and shale | *Most abundant sedimentary rock. Mostly clay minerals and mica flakes of very small size* |
| | | Bauxite | *Rare aluminous soil, important as an ore* |
| CALCAREOUS | | Marl | *A calcareous clay* |
| | $CaCO_3$ | Shelly limestone<br>Coral limestone<br>Algal limestone<br>Chalk<br>Globigerina ooze | *Examples of limestones formed from the calcareous skeletons or secretions of living things* |
| | | Oolitic limestone<br>Calcite mudstone | *Formed by partial evaporation of sea water* |
| | $+MgCO_3$ | Magnesian limestone<br>Dolostone | |
| SOLUBLE SALTS | $CaSO_4$ | Gypsum and anhydrite | *"Evaporites" i.e. rocks formed by the evaporation of sea water* |
| | NaCl | Rock salt | |
| CARBONACEOUS | | Coal and oil shales | *From land plants* |
| | | Petroleum (*in rocks*) | *From marine life* |
| IRON BEARING | | Oolitic ironstones<br>Hematite ores<br>Clay ironstones | *Marine iron silicate rocks* |
| | | Laterite | *Iron-rich tropical soil* |

# METAMORPHIC ROCKS

CHART 9

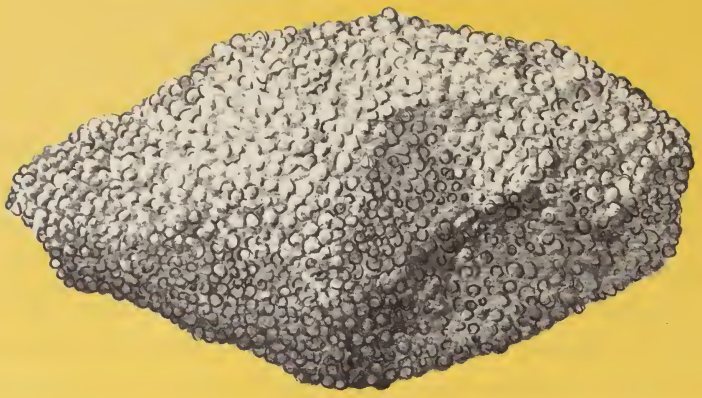
| Texture and mode of formation / Composition | *Recrystallization under movement* | | *Recrystallization without movement* | |
|---|---|---|---|---|
| | SCHISTOSE TEXTURE<br>*Platy or needle-like texture* | GNEISSOSE TEXTURE<br>*Mixed, layered, and irregular texture* | *High pressure*<br>GRANULOSE TEXTURE<br>*Grains not flat or long* | *High temperature*<br>MACULOSE TEXTURE<br>*Spotted or new mineral growth in all directions* |
| BASIC IGNEOUS ROCKS | Hornblende schist | Hornblende gneiss | Amphibolite, Eclogite | |
| ACID IGNEOUS ROCKS | | Granite gneiss | Granulite | Tourmaline granite |
| SILICEOUS | Quartz schist | | Quartzite | Spotted quartzite |
| ALUMINOUS | Slate, Phyllite, Mica schist, Garnet mica schist | | | Spotted slate, Hornfels |
| CALCAREOUS | Calc-schist | Marbles etc. | | |
| CARBONACEOUS | Graphite schist | | Diamond pipe rock | |

The object is usually to make a slice of standard thickness (almost exactly one thousandth of an inch). Rocks are very brittle, and such a slice has no strength in itself. The process depends on supporting it. The equipment needed will be some glass microslides (3 inches × 1 inch), some thin glass coverslips, a small supply of CANADA BALSAM (or Lakeside), two pieces of plate glass not less than 9 inches across mounted in shallow wooden trays, and a small supply of CARBORUNDUM powder in two sizes, coarse (grade 220) and fine (grade 500). In a geological laboratory the rock is cut and ground by diamond-armored saws and grindstones. This makes it much easier to get a good large slice from any chosen part of the rock. It is possible, however, with a trimming hammer to chip away at a rock specimen until a small thin chip about an inch across has been detached.

The next job is to grind one surface of this quite flat. If it is very rounded to start with, a carborundum wheel may be used at first, but the final stages at least must be done with a sprinkling of the coarse carborundum powder and water. Gradually a large flat surface is produced, but care must be taken not to wobble the chip while grinding, otherwise two surfaces, or a curved surface, will be produced. The surface is then washed free from all the coarser powder, and ground again on the second plate with the fine powder. After this it is washed again and dried. A large drop of Canada Balsam is then placed in the middle of the microslide and warmed on a hot plate until the Balsam is sufficiently cooked. The test for this is to take a needle and see if a thin streamer of Balsam hardens immediately on being pulled out. When this happens, the rock chip should be warmed and pressed firmly on to the balsam, which makes it adhere to the slide. Most of the remainder of the chip can then be ground away, holding it by means of the slide.

The final stages with fine carborundum should be done carefully

The composition-texture classification works well with metamorphic rocks. When the rocks have been altered completely the composition gives a clue as to what the original rock may have been, while the texture gives the best indication of the kind of metamorphism – especially the kind of stress and movement.



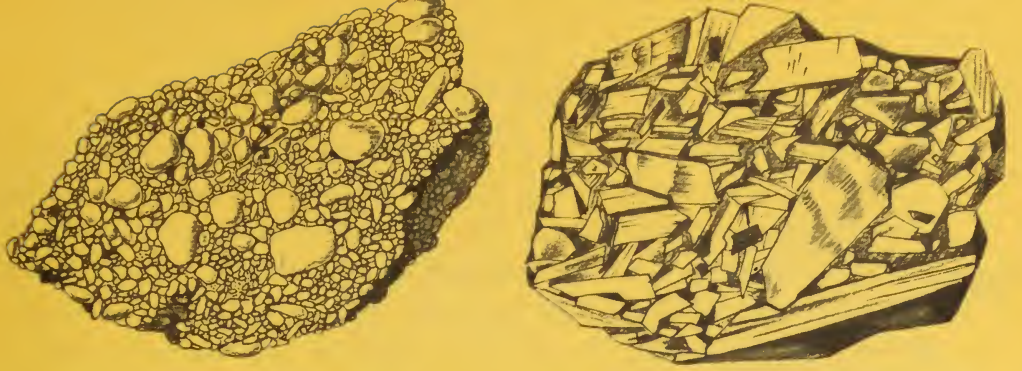
Oolitic limestone is so called because it resembles fish roe (Greek *oon,* an egg; *lithos,* stone). The small spheres of calcium carbonate (ooliths) grew by precipitation in warm shallow water, where sorting by current action concentrated a deposit of uniform texture, which gives a good building stone.

until the slice is thin enough for light to pass through it. To get the exact thickness a microscope must be used to check the final grinding – but in general it is a good plan to get the slice as thin as possible without letting it break up completely. More balsam is then warmed on top of the slice, and a coverslip is lowered and pressed down – carefully, so as to avoid capturing too many bubbles. Finally the slide should be cleaned up, and a paper label stuck on each end with information about the specimen. It is then ready for examination under the microscope or hand lens.

*Rock structures and textures*

The detailed study of rock composition by identifying minerals under the microscope, or by chemical analysis, depends on having some help and special apparatus. A great deal can be done in the field, however, by observing rock textures and structures.

Sedimentary rocks are usually distinguished by their layered arrangement known as BEDDING or STRATIFICATION. When the layers are very thin the rock is said to be LAMINATED, and each lamina represents a layer of deposit formed during a definite interval. The laminae are distinctive because some change took place at frequent intervals. For instance, in some lake deposits the annual floods evidently brought down coarser sediment than that deposited during the



Many rocks are composed of fragments of earlier rocks. When these fragments are rounded the sedimentary rock is known as a conglomerate, or solidified gravel, as shown on the left (its size could vary between a few inches to many feet). Angular fragments give a rock known as a breccia (right). Most breccias are sedimentary, but some are the result of earth movements and there are igneous breccias, too.

dry seasons. The variation in layers is particularly noticeable when deposits have been laid down in glacial (VARVE) conditions, for the summer melting yields sediment-laden torrents, but in winter only the finest particles remaining in suspension fall slowly to the bottom, forming a thin film of very fine clay. When the sediment is not so fine there may be many mica flakes in the silt, and these tend to lie horizontally, allowing the rock to split along the bedding. When a rock splits easily it is said to be FISSILE, and when it does not split it is MASSIVE.

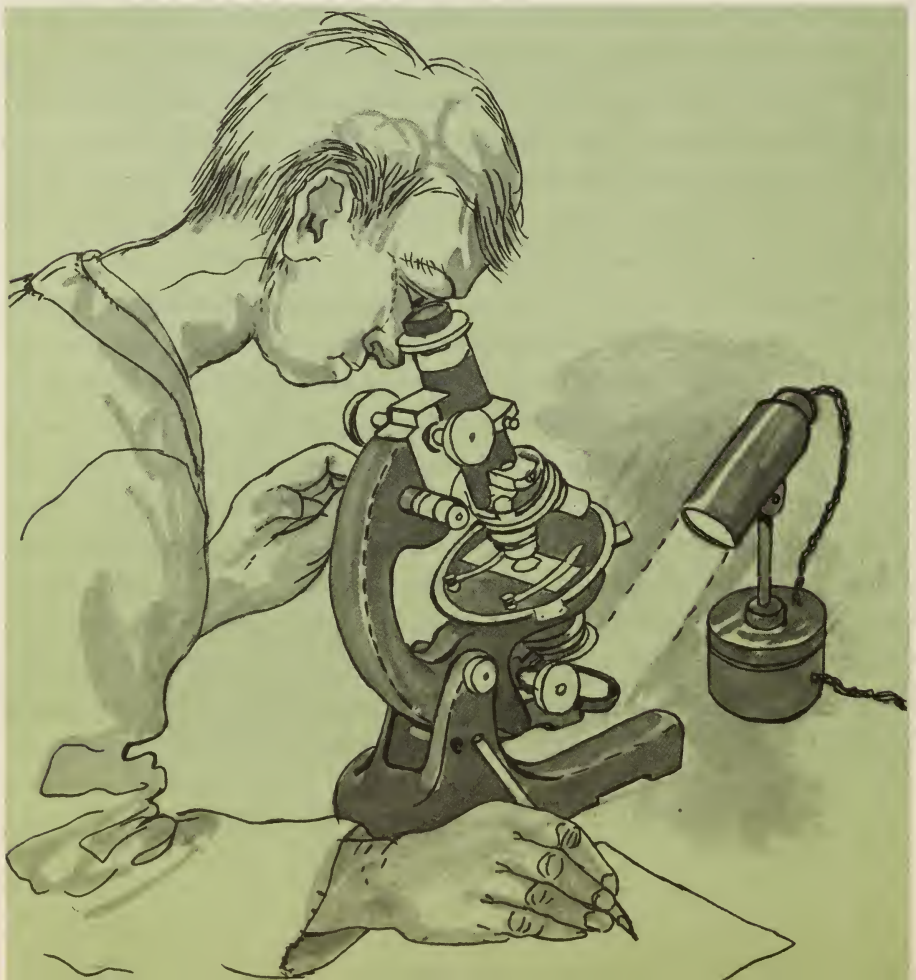
JOINTS are cracks, other than bedding planes, along which a rock breaks. Most rocks are well jointed. Joints commonly run in two or more parallel "sets" and are often at right angles to the bedding. In this way bedding and jointing together lead to the breaking up of rock into blocks, which are often nearly rectangular and may occasionally be picked out clearly by weathering.

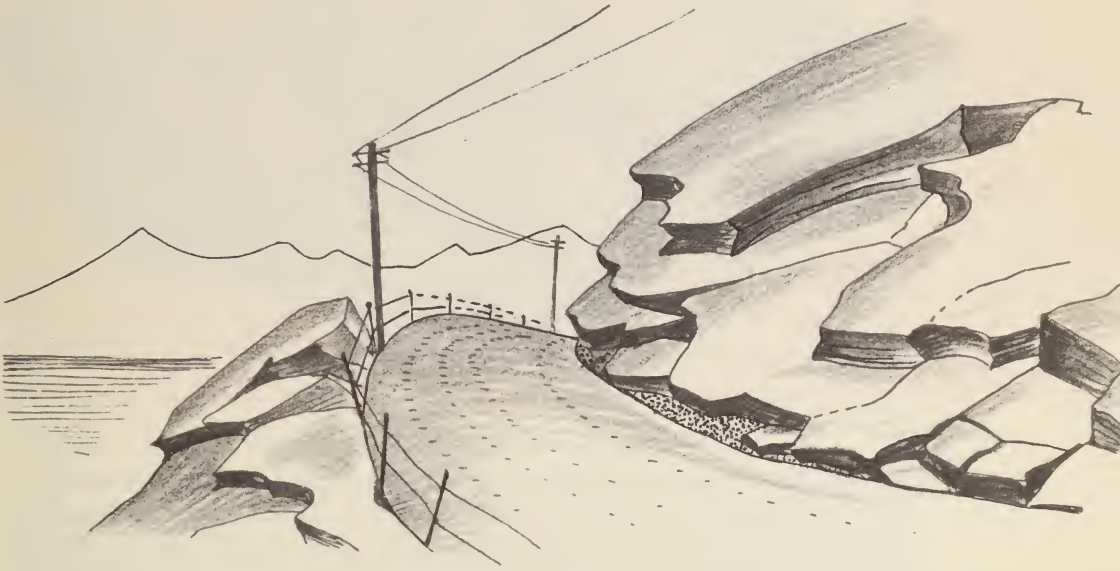
Examples have already been mentioned of structures which indicate the top and bottom of sedimentary layers. There are also many other interesting structures to be observed in sedimentary rocks, such as the small-scale folds and contortions found in SILTSTONES. These may indicate a disturbed state of sedimentation, possibly due to SLUMPING – or the sliding or newly-formed sediment down a submarine slope. Slumping can be distinguished from folding, which is due to earth movements, in so far as it is overlain by unfolded rocks.

Many sedimentary rocks contain hard nodules or CONCRETIONS. These are sometimes regular spheres like cannon balls, but others assume quite fantastic shapes. They are usually due to concentrations of some constituent of the rock around a number of centers – often fossils – so that on breaking open the concretion an interesting discovery may be made. SEPTARIAN concretions, for instance, reveal a network of open cracks filled by clear crystals, as though the concretion had shrunk after the formation of its hard exterior, and the cavities caused by the shrinking had been filled later by percolating solutions. Concretions may be concentrations of calcium carbonate, silica, iron sulphide or other constituents dissolved out of the rocks.

Much may be learned about conditions of sedimentation from the

The picture of a petrological microscope in use shows some features which distinguish the instrument from the usual biological microscope, such as the rotating stage and the optical plates which slide in the tube for use with polarized light.





The rock is breaking parallel to the hillside. This kind of jointing, or sheeting, is typical of massive rocks like granite, and is a kind of large-scale exfoliation due to the expansion of the rock following the removal by erosion of the overlying material which was compressing it.

nature and shape of the particles or pebbles, if they are large enough to distinguish. Ice-scratched boulders, ventifacts, polished and rounded sand grains, "DERIVED" FOSSILS (apparently eroded from an earlier rock), or pebbles of a distinctive rock known only from a particular locality, may all be used to interpret the geographical circumstances at the time of deposition.

Igneous rocks, on closer study, also show many features useful in interpreting the conditions of their formation. The grain size gives some idea of the rate of cooling (e.g. large crystals grow slowly). Many igneous rocks show two generations of crystals. The large crystals (known as PHENOCRYSTS), commonly of feldspar, were formed first, possibly at a time of slow cooling. Then, when a lower temperature was reached, possibly by rapid cooling on intrusion into cold rock, the remainder of the rock solidified into much smaller crystals. The finer crystals, or GROUND MASS, give some idea of the

The spherical lumps are a series of connected concretions of dolomite separated from a solid mass of limestone. Concretions are concentrations of some mineral matter from the whole rock into peculiar shapes within it. Many odd shapes are possible. Concretions often contain fossils or mineral crystals and may be worth breaking open.

final rate of cooling, and determine whether the rock is classified as coarse, medium, or fine-grained. Any of these types may have phenocrysts. This texture, with two generations of crystals, is known as PORPHYRITIC TEXTURE.

Another common texture, almost entirely restricted to lavas, is VESICULAR TEXTURE. This is the "frozen" froth, or consolidated lava full of gas bubbles, known as PUMICE. In the course of time, after such rocks have been buried and soaked in percolating ground water for ages, the small bubble cavities become filled up with a secondary mineral, such as calcite. The fillings are known as AMYGDALES, and the rock is then known as amygdaloidal – indicating that it was once vesicular. An amygdaloidal basalt was almost certainly a basaltic lava, whereas a basalt without this texture could be either a lava or an intrusive rock such as occurs in a dike or sill.

The edge of an igneous rock may give some clue to the nature of its formation. If it has been cooled against another rock – as when intruded into cold rock, for instance – the edge of the igneous rock may be finer grained than its interior, and may even be glassy. Such

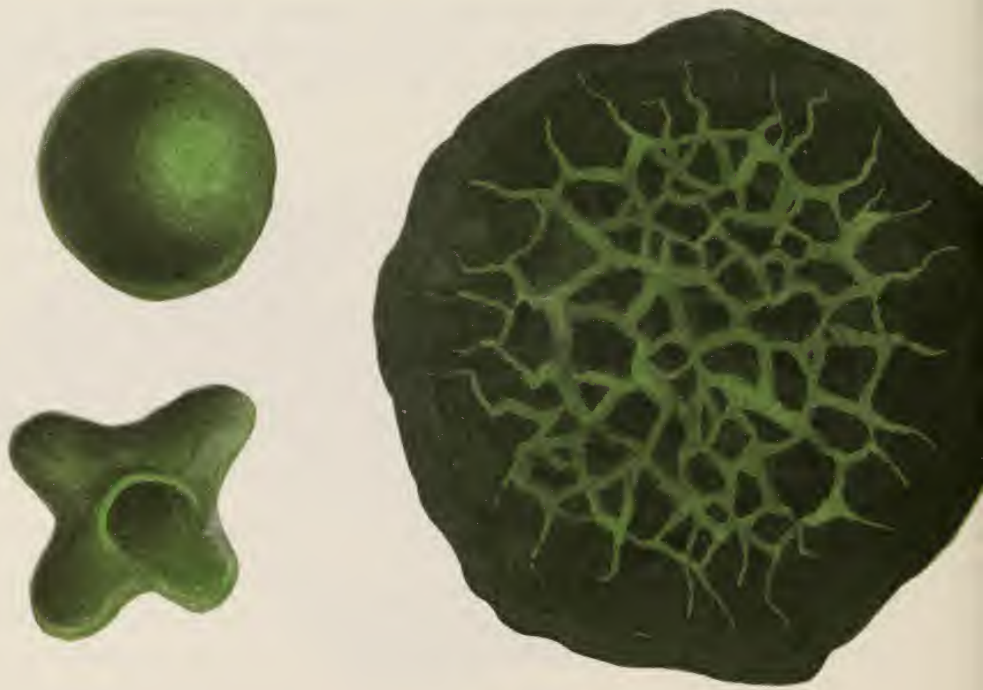
edges are known as CHILLED MARGINS, and the rock against which they have cooled often has a corresponding BAKED MARGIN because it has been heated sufficiently to cause metamorphism. A red sandstone may be bleached by CONTACT (or THERMAL) METAMORPHISM in this way. The baking of the margin may make the surrounding rock more resistant to weathering, while a dike itself may weather easily, so that the effect produced by a small dike crossing a stream or a shore may be seen as the baked walls on both sides of a trench. Another marginal feature to be seen in igneous rocks, particularly in plutonic rocks, is the inclusion of lumps of the surrounding rock which have become detached and drifted into the magma. These are called XENOLITHS, and are often found near the top of a granite intrusion.

When a lava is ejected under water, the water cools its surface very quickly and a skin is formed into which more lava is forced, as into a balloon, until it can hold no more. It then rolls away, to give place to a new sack, which fills up with more lava – and so on. The result of all

A relatively white sandstone with concentric shells of iron oxide staining. It appears that the iron migrated in solution from the remainder of the rock, and then was concentrated in the interstices between the sand grains, in a series of spherical concretions.

this is to pile up a deposit of these PILLOW LAVAS, as they are called, which looks like a pile of sandbags. Larger lava sheets without this structure may also have flowed under water.

Very rapid cooling of magmas or lavas may not give any opportunity for crystallization at all, and then an igneous GLASS is formed. A glass is not stable for very long, and in the course of time minute crystals begin to grow; it is then said to DEVITRIFY. An igneous glass is therefore not likely to be an ancient rock – certainly no older than Cenozoic. Older rocks which have once been glasses may be recognized by their very small crystals – hardly distinguishable under the microscope – and more particularly by their small spherical concretion-like structures known as SPHERULITES. These are spherical growths of crystals radiating round a series of centers.



Examples of concretions from sedimentary rocks. The one on the right has been broken through the middle and polished. The cracks are filled with a later mineral such as calcite, and show that after the concretion was formed the material within it shrank, leaving spaces to fill with later mineral. This kind is called a septarian concretion or nodule.

This illustrates the trimming of a specimen to the desired shape. The rock is best held by hand, away from the eyes, and short sharp blows knock off succeeding chips from the underside of the exposed corner. Ideally the finished hand specimen shows no hammer marks.

Thus within igneous rocks we may find three different kinds of spotted texture: porphyritic texture distinguished by the crystal shapes of the phenocrysts, amygdaloidal texture distinguished by the rounded shape of the amygdales, and spherulitic texture distinguished by its regular spheres, the radiating crystals of which pass without any clear boundary into the texture of the rock.

Some igneous rocks show evidence of the flow in the magma before it solidified. This may be by the arrangement of flat crystals, or, in fine-grained rocks in particular, by a pattern of streamer-like colored bands. Flow patterns are easy to distinguish in rocks which were once glassy, such as RHYOLITES.

*Textures and structures due to deformation*

The textures of metamorphic rocks have already been referred to, and the common metamorphic rocks, classified on this basis, are tabulated in Chart Nine. There are also other rocks, not included in the chart, which have been intensely crushed but not recrystalized. In a fault, for example, where the two sides have rubbed together, the rock may be ground down to a MYLONITE with a very fine texture. This is common in thrusts where large slabs have been pushed one over the other. On the other hand, where the earth's crust has appa-

rently cracked under extension rather than compression, the rock in the fault is simply broken into irregular pieces – possibly with spaces between them – and this is known as a FAULT BRECCIA (breccia is the name of any rock made up of angular pieces, however they may have accumulated). Where rock surfaces have moved over each other a polished surface may be produced, usually striated with distinctive groovings known as SLICKENSIDES.

Rocks break by jointing and, under continued pressure, by faulting. (Some different kinds of fault are explained in the glossary.) Under still greater pressures, at great depths in the earth's crust, rocks are deformed by bending rather than breaking and this takes place by a kind of flow movement – almost as though the rock were a stiff fluid. A very long time is necessary for this to happen, and the same stresses, applied more quickly, might break the rock. The effects of this kind of solid flow are seen in the metamorphic textures – particularly in the schists, gneisses and GRANULITES.

The texture known as SLATY CLEAVAGE shows an intermediate stage between a clay or shale and a schist. Rock cleavage is of several kinds, some of which may be grouped together as FALSE CLEAVAGE, in which the rock will split only along certain distinct planes. These planes are usually at an angle to the bedding planes, and are due to a shearing or sliding movement in the rock which results in the rock splitting along closely spaced parallel planes. TRUE CLEAVAGE, on the

Thin section of quartz porphyry, as seen through a microscope (x 20). The texture suggests an igneous rock, and according to Chart 7 the many quartz crystals (phenocrysts) would make it an "acid" rock, and the fine-grained ground mass would then place it in the rhyolite family of rocks.

Thin sections of pitchstones (x 50), which belong to the rhyolite family. The rock is glassy, with minute crystals growing in the glass and combined in the various patterns shown.

Thin section of a spherulitic granophyre (x 20) also belonging to the rhyolite, or micro-granite, family. The radiating clusters of crystals (spherulites) give a black cross when the polarizing and analyzing attachments of the petrological microscope are used. The feldspar crystals grew out from centres as the magma finally solidified.

other hand, is due to new flat minerals growing in the rock in such a way that they are arranged perpendicular to the direction of the greatest pressure. In true cleavage, then, because of the arrangement of flat minerals, every part of the rock will split, and always in the same direction, parallel to the inherent grain as in slate. When such slates have been formed out of very fine-grained clays in the first place, they may split with perfect regularity and this, as we have seen, makes them invaluable for use as roofing slates.

Rocks are more usually deformed by folding. This may be accom-

panied by faulting, jointing, and false cleavage, if it takes place within a few thousand feet of the surface of the ground. When folding takes place at greater depths, the rocks change their shape by flowing without breaking. A great deal can be found out about the way in which the earth's crust has been squeezed and contorted by a study of the shapes of folds and faults, which at first are more easily seen from a distance but should be studied at close quarters for the texture and small-scale structures of the folded rocks. This aspect of structural geology leads on to ideas of how the rocks in the earth's crust have moved, and consequently how the different parts of the earth itself have moved in relation to each other. Movements have occurred throughout geological time, and are still going on, as is shown by the uplift of mountains and in the microscopic texture of the rocks which form them.

Thin section of obsidian, a glassy volcanic rock of the composition of granite. Some quartz crystals had formed and the fluid flow around their centers was "frozen". Such flow structure is typical of fine-grained volcanic lavas.

# 19. Exploration

This last chapter considers how you can put together the various observations you make, and the records of the specimens you collect, into the single study of a region. Such a piece of work is known as a survey, and very often – but not necessarily – involves making a map. Whether the area studied is being visited for the first time by man or is thickly inhabited, you are exploring, for there is always something new to be found.

*Geological maps*

Before attempting to make your own survey it is worth getting familiar with the idea of a geological map by examining one of an area you know. The various symbols are explained in the margin of the map. The colors represent rocks which are given formation names and are arranged as far as possible in order of age. The color pattern represents the OUTCROPS of these different formations at the surface, just beneath the soil. Areas in which no rock is exposed at the surface may be included in the coloring, but any particular rock shown on the map should be found on digging down beneath the soil. Such outcrops have been plotted by first marking on a map the kinds of rock found along any streams, cliffs, shores, quarries, road-cuts or other exposures in the area. Then, if there were sufficient exposures, the pattern of the outcrops was drawn in by joining up the geological boundary lines across the areas where the rocks were covered by soil and vegetation or buildings.

Large-scale maps are the best when examining rocks in the field, as more detail is given of where the rocks may be exposed. Take trouble to fold them so that any part can be referred to easily in the open. Small-scale maps are useful for study, for reading, and for general information about the area, but they are not of much use in the

field. In the first place, the small scale means that details cannot be given, and very often the different rocks of a series are grouped together under one color or ornament, and small outcrops are omitted altogether. Then again, surface deposits such as alluvium in river valleys, fluvio-glacial gravels and boulder clays, may obscure the underlying rocks and would be shown on a large-scale map but not on a small-scale map, where only the underlying rocks or SOLID GEOLOGY can be shown. This solid geology may be the most important thing to show, but it is not what you can find easily at the surface.

The folios of the U.S. Geological Survey are well worth studying, for they give full topographical and geological maps of any particular rectangle, together with sections and special maps of sub-surface structure and a written introduction to the geology of the area. The only difficulty is that, in common with nearly every country in the world, the U.S.A. has not yet the whole of its area covered by detailed geological maps, and there is a chance that the area in which you are interested has not been surveyed in this way. If it has, you are very fortunate, but if not you may still be able to find a detailed map in one of the geological journals published – such as the *Bulletin of the Geological Society of America*.

If you can find some geologist who knows the area you will be able to get help on this point, which will save you much effort in the long run. Also, you may well strike up a valuable friendship in the process. Help from an expert applies not only to maps but to all the voluminous geological literature which may be published about any area, and which is sometimes so difficult to get to know. A careful exploration of the literature allows you to make the best use of your time and the most useful discoveries in the field.

Geological maps provide a great deal of information for those who can read them properly, but to do so takes a lot of practice, just as it does to read a written language. You will gradually be able to visualize the arrangement of the rocks from a glance at the geological boundaries in relation to the topography. To do this sometimes involves some understanding of the geometry of rocks. There are ways of depicting the structures by representing rock surfaces by contours, known as

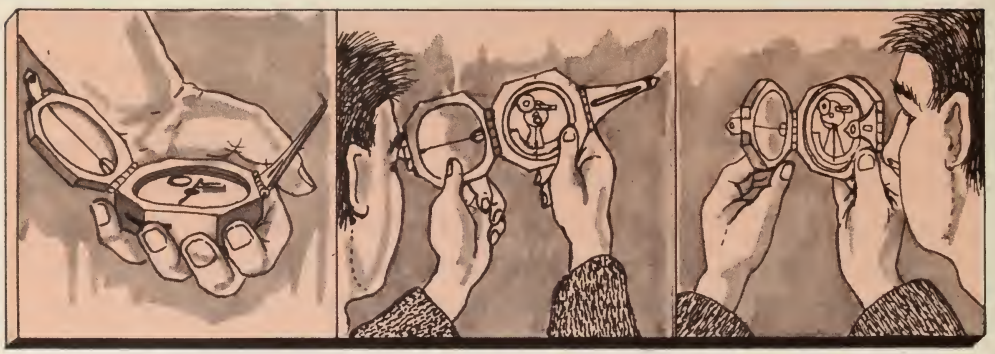
STRUCTURE CONTOURS, in the same way that the shape of land is shown by topographical contours. You will be surprised how much may be discovered about the rock structure in this way, if sufficient information is given on the map in the first place. By this means geologists draw accurately the rock structures found, and predict where a particular rock may be found elsewhere on the map or at some depth below ground. This is another important aspect of the study of structural geology which can only be mentioned here.

*Surface exploration*

When examining an area for yourself you may have to start out without even a map of the topography, and the first job which many a geologist has to do is to make a base map on which he can put his findings. This is usually done by a specialist surveyor. Often now the detail is built up from a set of aerial photographs taken from aircraft by large cameras pointing vertically downwards so that the photograph is itself something like a map and can be used as such in the field.

Even if a map exists you will still have to find just where you are on it, and it is advisable to get to know how to make a sketch map and improve on it by a few simple survey methods. For instance, you can get into the habit of pacing and estimating distances, which is far better than nothing and, with experience, can be remarkably accurate. You can use a simple PRISMATIC or a BRUNTON COMPASS for taking bearings and building a network of triangles between various points, and so form a skeleton around which the map can be sketched. In hilly country an aneroid barometer or ALTIMETER is a great help in finding the height – provided you take care to keep checking it against known points, for it varies with the general changes in atmospheric pressure (which it is, in fact, measuring). For detailed collecting, a tape measure will be useful for getting exact thicknesses of strata and distances between one point and another. You can also mark off a few notches in inches along your hammer shaft.

Some idea of the geological structure of areas where the rocks are unexposed may be obtained from trenches, post holes, or other temporary excavations; otherwise a SOIL AUGER can be used. An ordinary



Three figures show the Brunton compass in use in the hand – left: taking a rough bearing; center: measuring an apparent dip of distant rocks; right: for sighting a vertical angle. It can be laid on a rock surface to measure strike and dip directly.

carpenter's auger will do for this purpose, though it may need to be welded to a rod, giving a total length of about three to four feet The diameter should be between half an inch and an inch. With a short wooden handle it can be screwed down into the soil and pulled up with a sample of the lowest material penetrated. This is very helpful in mapping a small area where the rocks beneath the soil are soft and of distinctive color. The color of the soil, particularly in arable land, may itself indicate what rocks are underneath, if the rocks are of distinctive color. There are, however, only limited uses for the auger, as many rocks are too deep, too tough, or too difficult to distinguish by this means.

When an exposure of solid rocks is found there will usually be some directions worth recording, such as bedding, or jointing, or cleavage. The standard method of doing this is to measure the DIP and STRIKE of each surface, and record them on the map and in the notebook. The strike of a rock surface is the direction of a horizontal line in it, and this is usually given as an angle measured from magnetic north, that is, the reading of a compass when the compass is laid along the horizontal line. The horizontal strike line may be found by using a level or CLINOMETER. Sometimes the problem is solved automatically when the water level of a stream or a lake passes across the rock surface,

giving such a line. However, a clinometer is needed in any case to measure the dip of the rock surface, which is the angle between the greatest slope of the surface and the horizontal. A simple clinometer may be constructed from a protractor with a plumb line hanging from its center, but geologists usually find some form of spirit-level better. This may be in a separate instrument, or it may be combined with a compass so that both compass and clinometer are in the same instrument. Such a device is the Brunton Compass, an instrument which is widely-used in field geology, for measuring both the dip and the strike of a rock, for sighting horizontal and vertical angles to find dips and strikes from a distance, and for elementary survey. The results are usually plotted on a map as small dip arrows or signs, and when dips have been measured at many points over the ground the pattern of folding can be seen roughly, or even worked out by accurate geometrical drawing.

The measuring of dip and strike is only one of many kinds of obser-

Geologist's pocket Brunton compass-clinometer. The spirit level scale is attached to a lever moved from behind for measuring vertical angles, and the compass needle gives horizontal angles. The lid has a mirror which is useful for sighting.

vation to be made. Naturally notes will be made of the nature of the rocks, and specimen numbers will be recorded on the map and in a notebook. Surface features should be noted and sketched, such as the kind of hills, cliffs, and streams. Very often a particular surface feature, such as a ridge or gully, may be the surface expression of a structure in the rocks beneath, perhaps a fault. Thus the land forms are both an aid in interpreting the solid geology beneath and also interesting in themselves, for they give an indication of the activity of the surface forces and their effect on the underlying rocks.

*Sub-surface exploration*

Opportunities for exploring underground are rare. *Tom Sawyer* gives some idea of the hazards of underground caves, which often trace the course of subterranean waters and are usually found in limestone rocks which readily dissolve away. Mines give a very detailed picture of the sub-surface structure, for in their tunnels the rocks can be examined carefully. Areas which have been thoroughly mined for some time therefore yield knowledge of the underground structure in more detail than elsewhere. (But if you explore old mines, make sure to get official permission first, and find out if the mine is safe.)

A great deal of money is expended on drilling, for mines, for water, and for oil. In some cases the drilling is purely exploratory, to find out what rocks may be found at what depths, but there is always the chance of finding some valuable material by a lucky strike, as, for example, when an oil field is punctured and the exploratory hole yields petroleum at high pressure. Some millions of miles of drilling have been done in the earth's crust, and the information acquired from this drilling is one of the most important contributions to geological knowledge. Because so much money is involved in deep drilling, many ingenious and patent devices have been developed to cheapen this very expensive process.

From a geological point of view it is best to have a continuous core from the surface, but this is very costly, because after every ten feet or so of coring the coring tool has to be lifted up from the bottom. This necessitates unscrewing the long rods in, say, twenty-foot lengths,

one by one, to recover the core, and then screwing them on again while the coring tool is once more lowered to the bottom. For shallow wells a simple percussion drill can be supported by a cable and allowed to fall, like a pile driver, and scoop out the material at intervals. Most deep drilling, however, is accomplished by a rotating bit with hard steel teeth, on wheels fixed at an angle. The bit rotates, and with the weight of the rods above it bears down on the rock and grinds it away. From the center of the bit comes a supply of very muddy water which has been pumped down the rods and is then returned to the surface up the outside of the rods. This mud suspension is dense, and so brings up the powder and chips detached by the teeth. The method is quick because the drill goes continuously downwards without having to be returned to the surface except for repairs and renewals. It has the disadvantage, however, that only small fragments of rock can be collected at the surface. Many elaborate laboratory techniques are used to make the most use of these samples. Among other things, the study of microfossils is very important, for they will be the only kind of fossils identifiable after such drastic treatment. There are also electrical devices which can be lowered down the hole. These record on strips of paper, moving as the instrument is lowered, a complex set of curves indicating some properties of the rock through which the instrument is passing. Such records may be interpreted to give much information, and together with what else is known may even lead to identification of the different rock layers.

These methods are mentioned not because you can afford to carry them out for yourself, but because so much drilling is done that there is a good chance sooner or later of being able to watch it going on. Usually there is a geologist with the drilling team who may be able to help you. Besides, it is of interest to know how a considerable part of the cost of gasoline is spent.

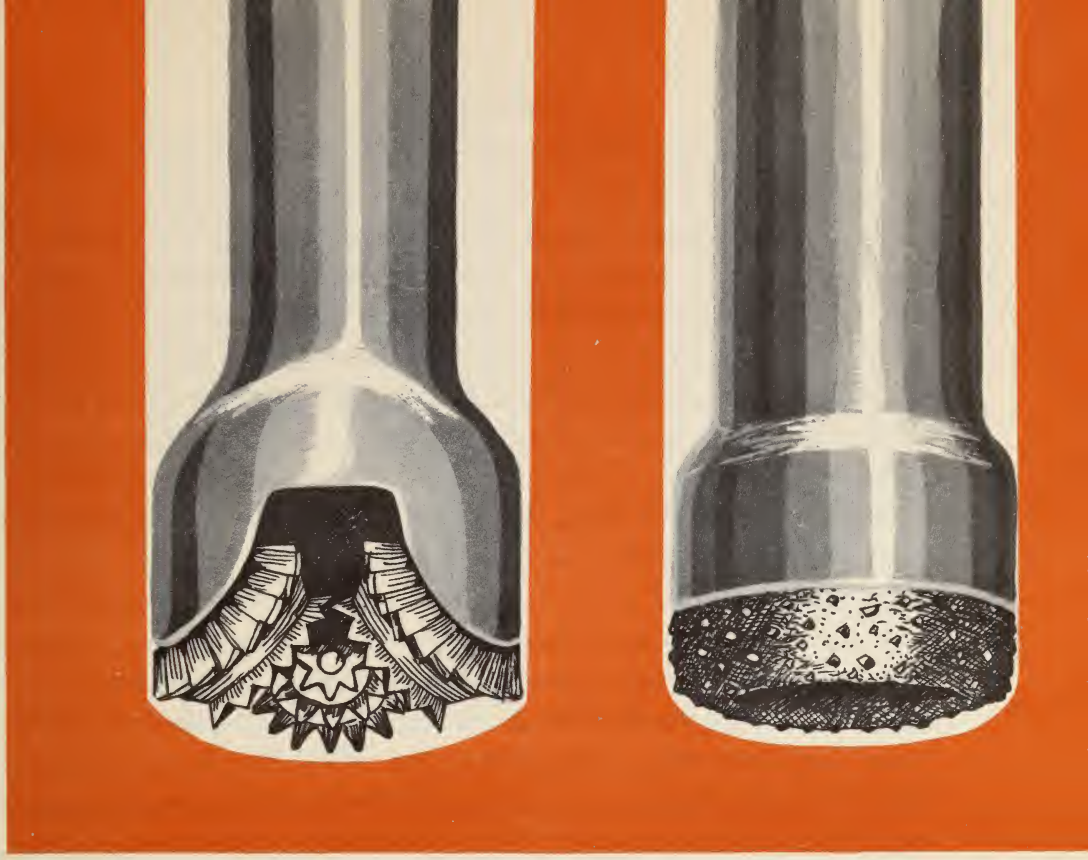
*Geophysical exploration*

To drill deeply is so expensive that other methods, themselves quite expensive, have been devised to find out about the rocks deep down without actually drilling. Here again you may easily meet a team of

scientists engaged in this kind of exploration, and be able to learn much from them. By geophysical exploration we mean some method of surveying certain physical properties at the surface and of inferring from this something about the state of affairs below ground. Often the results do not tell much by themselves, but taken together with what is already known or suspected the next step in sub-surface exploration may be suggested, e.g. further surveys or a test-drilling at some point. There are several methods used in geophysical exploration, each of which will receive only brief mention in the following paragraphs.

Gravity surveys have already been mentioned. These are relatively cheap, for the GRAVITY METER, though very expensive, is small and can be taken around in a small vehicle or even carried. Two or three men with one vehicle may measure gravity at as many as fifty stations a day. They have to keep returning to certain standard stations, for the spring in the instrument is so sensitive that the measurement varies even at the same place. The surveyors must know just where on the map they are measuring gravity, and also exactly how high above sea level they are. Thus in out-of-the way country there may be a survey party associated with a gravity team. A great deal of calculation is necessary when they return to their center, for in each measurement they have to allow for the variations in the instrument, the altitude above sea level, the latitude, and the attraction of the hills and valleys – and this may be the most tedious part of the operation.

SEISMIC SURVEY is a much more expensive and elaborate kind of work. The same principle is used as in the study of earthquake waves, but seismic survey makes use of artificial disturbances, in the form of explosions which can be released at required places where very sensitive GEOPHONES have been set out in a line or pattern. A high-speed recording instrument is switched on for a short time, beginning a second or so before the explosion. The moment of the explosion is relayed to the recording instrument by a wireless signal transmitted when a wire wrapped round the charge breaks. Each geophone, in a known position, is connected with an amplifier, which magnifies the small vibrations of the ground, to signals recorded on the fast-



Two kinds of rock-drilling bits are shown. The one on the left with wheels of hard steel teeth grinds the rock away, and chips are washed up the borehole by a jet of muddy water. The other is impregnated with diamond and cuts a solid core, which is pulled up in lengths.

moving paper as measurable waves. These waves have higher frequencies than those of earthquakes, and are more suited to the detailed exploration of a small piece of the earth's crust.

Indeed, the normal seismic methods are a kind of miniature earthquake study. Changes in wave velocities caused by discontinuities can be detected a few hundreds of thousands of feet down (instead of tens or hundreds of miles) and this kind of information allows geologists to relate the discontinuities to rock horizons known from previous deep drilling. A REFLECTION method is used with the shots near the geophones, in which the sound waves traveling down are reflected upwards from a succession of discontinuities and then recorded in a

spread of geophones. The principle is similar to the method of echo-sounding used at sea.

Refraction methods may also be used, in which the recording apparatus is at some distance from the shot point, and the waves travel both along the ground and under it. If the waves travel faster at depths than they do on the surface, it is as though the waves were catching a fast underground train which gets them to a distant point more quickly, in spite of the time taken to go down and up at each end of the journey.

From many records at the surface, taken at different distances from the shot, it is possible to calculate the depths of the different layers, the velocity of sound in them, and the slope of their boundaries. This information can be matched against information from a boring, so that results from the boring can be extended outwards into the surrounding country, and the location of the next bore-hole decided. A seismic team requires a large number of men and vehicles, for drilling the holes for the shot, for carrying explosive, for the recording apparatus with darkrooms, and for the many miles of cable used to connect the geophones. All this costs a great deal to maintain, but it may still be cheaper than drilling deep wells at frequent intervals.

The same method on an even more elaborate scale has been used for exploring beneath the sea floor. To save having ships at many different recording stations, each receiving apparatus is in a separate float and is linked with a radio-transmitter for relaying the impulse to the parent ship. A small boat may then let off charges at various distances, or the charge may itself be detonated by radio. This type of exploration is on a scale intermediate between earthquake studies and routine seismic exploration on land. At sea larger explosions can easily be used and the rocks below probed to greater depth. The same general methods have been used in the study of the depths of the great ice sheets of Antarctica and Greenland.

Electrical surveys are used in exploration for water in desert regions, by measuring the resistance to electrical currents which the ground offers. When the ground is wet it passes a current more easily, so a current is passed into it at two electrodes some distance

apart, and the flow of electricity between them is measured. This is only of limited use on the surface, but is important when applied to survey of wells, down which the electrodes may be lowered and a continuous record obtained.

Magnetism is used in a number of kinds of survey. It is well known that the angle between MAGNETIC NORTH and true north varies in different parts of the earth's surface, as also does the dip of the magnetic needle measured from the horizontal. Moreover, magnetic force varies in intensity, and all these characters change from day to day and from year to year. These surface variations are due to the earth's magnetic field as a whole, rather than to changes in the rocks at any particular point.

However, the rocks do have some magnetic effect. This has long been made obvious in the course of exploration for magnetic iron ores, but now very delicate instruments have been devised to obtain magnetic information about deep rocks. This kind of survey depends partly on the behavior of rocks, which act to some extent as permanent magnets. The MAGNETOMETER used is quite small and can easily be mounted on a tripod and read quickly. Even more important has been the later development whereby a magnetometer is towed behind an aircraft or ship, enabling vast areas to be surveyed in a short time.

In a new kind of study it has been found that the direction of magnetization of a rock is governed by what the magnetic field of the earth happened to be at the place and time the rock was formed. In spite of many difficulties this method enables us to study fossil magnetism. It may turn out to be significant, for if the magnetic poles have always been somewhere near the axis of rotation of the earth, as seems likely, then we have a means of finding the direction of a particular rock and the distance from the pole when it was formed. This has become important because results available suggest that the poles were not always where they are now in relation to the continents. The differences may be due to the earth's surface moving round the spinning earth as a whole, or to different parts of it moving differently as a result of continental drift.

The study of fossil magnetism (or PALEOMAGNETISM) is not yet

very far advanced. It is carried out by collecting large specimens – about the size of a half-brick – from any rocks which have a trace of iron in them, in such a way that their exact position and direction are known. They are then taken to the laboratory, where their magnetic direction is measured. This is then interpreted in relation to the original arrangement of the rocks on the earth's surface.

Since nuclear power has become so important, rocks containing minute traces of uranium and thorium may be valuable. These can be detected by RADIATION COUNTERS, now widely sold as portable electronic boxes. Wearing earphones and passing the probe of the instrument over the ground – or simply carrying it in the back of an automobile or in an aircraft – any amateur can gauge the amount of radiation, and may be lucky enough to discover a new deposit of radio-active material by merely hearing a rapid increase in the number of clicks through the earphones.

There are many other ingenious methods for exploring the crust of the earth which depend on co-operation between scientists of quite different specialities. Chemical methods for detecting traces of various materials have been developed, so that ore-bodies can be detected some distance away by their effect on the composition of the soil. Another field of chemical study is that of very complex ancient living substances which have been preserved almost without change. But all these methods still depend for their interpretation on the understanding of elementary principles concerning rocks, minerals and fossils, and on reliable collecting and observing in the field.

*The spirit of exploration*

Exploration, whether it be traveling to unvisited lands or looking more closely at what is around us, is an activity which all can share and enjoy. It is exciting to make a discovery that is entirely new to man, but whether or not an observation or theory is made for the first time, it is the first time for the individual who makes it. We must discover the world ourselves to share in the knowledge of it.

Truth is of many kinds, or many-sided, and man distinguishes himself by his striving after it. Ultimately there is only one truth, and this

belief has prompted men throughout the ages to seek it, for in the light of one truth they believe that difficulties and contradictions may be resolved. Contradictions become a stimulus to further discovery, presenting a challenge similar to the blank on the map which leads an explorer onwards. The belief that there is a solution, and that the solution is worth seeking, is part of the excitement of discovery.

What has been discovered, and is still being discovered, is a world of splendor, linked with thousands of millions of years of history, and set in space through which light has been traveling for thousands of millions of years – a world in which the crystal and the micro-organism each has its story to tell. The excitement of discovery is properly linked with a sense of wonder and humility in the face of this splendid creation.

# Glossary and Index

This is an index to most of the technical words in the book, especially where first used. Page references in *italics* refer to the charts and illustration or their captions. The index has been converted to a glossary by adding some brief explanations. Further explanation of these entries may be found by reference back to the text, chart or illustrations, or to other entries. Where two words are found in the text such as *primary wave* it may be necessary to look up under the second word.

Chemical formulae are in square brackets throughout, and generic names of fossils in *italics*. The *Glossary of Geology and related sciences* (Washington) is the best book for reference.

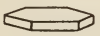
**acid igneous rock** *210*, with more than 65% silica e.g. granite, rhyolite.
**Agassiz, Louis** 17, (1807–73) Swiss, later American, paleontologist.
**agate** 160, *161*, common form of mineral chalcedony, a semi-precious stone. [$SiO_2$]
**agglomerate** *213*, a volcanic breccia composed of bombs, lapilli, and dust.
**aggradation** 76, a word for sedimentation emphasising the building up of the crust.
**albite** 204, [$NaAlSi_3O_8$] a soda plagioclase feldspar.
**algae** *101*, 125 a lowly kind of plant. Some kinds precipitate calcium carbonate.
**alloy** 175, a man-made metallic mixture.
**alluvium** *70*, 71, deposit formed by streams in river valleys.
**altimeter** 229, a barometer used to measure height above sea by air pressure.
**aluminous rocks** *213–4*, rocks rich in aluminum.
**aluminum** *56*, 178, metallic element [Al].
**amethyst** *37*, 198, Variety of quartz [$SiO_2$] colored by traces of manganese.
**ammonite** *132*, 133
**Amphibia** 131, *195*, a class of vertebrate.
**amphibole** 204, *206*, a family of ferromagnesian silicate minerals e.g. hornblende.
**amphibolite** *214*, a metamorphic rock with much hornblende.
**amygdale** 220, a mineral filling of a gas cavity, or vesicle, in lava.
**amygdaloidal** 162, with amygdales.
**andesite** *210*, a fine-grained or volcanic intermediate igneous rock.
**anhydrite** *206*, *213*, a mineral [$(CaSO_4)_2 H_2O$] formed by evaporation of sea water.
**animal kingdom** *195*
**anorthite** 204, [$CaAl_2Si_2O_8$] a lime plagioclase feldspar.
**Anthozoa** *195*, a class mainly of corals.
**anthracite** 179, a coal with high carbon content due to pressure of rocks.
**anticline** *92–3*, an upward fold.
**apatite** 199, a mineral [$Ca_5(PO_4)_3F$]; important source of phosphorus.

**aragonite** 32, a mineral [$CaCO_3$] similar to, but less stable than, calcite.
***Archaeopteryx*** 134, *135*, a fossil bird.
**Archeozoic** *154*, a Precambrian Era.
**argon** 54, a chemical element [A]; an inert gas.
**arkose** *213*, a coarse-grained sedimentary rock with much quartz and feldspar.
**armadillo** *16*, a modern mammal.
**artesian well** 168, *172*.
**Arthropoda** 129, *195* an animal phylum.
**asbestos** 204, an amphibole mineral, with long fibrous crystals, used for fire-proofing.
**ash** *213*, a volcanic dust.
**asteroids** 103, about 1500 minor planets between Mars and Jupiter.
**Asteroidea** *195*, a class of echinoderm.
**astronomy** 20, 102.
**atmosphere** 44, the layer of air enveloping the earth.
**atoll** *76–7*, 118, a coral ring-shaped island with a lagoon in the middle.

**atom** 31, the smallest particle of a chemical element. It may be divided further into protons, electrons, etc.
**augite** 204, a pyroxene mineral common in basic igneous rocks.

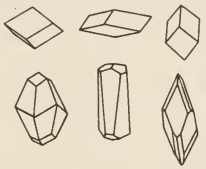
**badlands** 164, soft rock country deeply eroded by torrential streams associated with soil erosion.
**baked margin** 221, where igneous material has metamorphosed the country rock.
**barchans** *119*, a kind of sand dune.
**barite** 202, *206*, the mineral "heavy spar" [$Ba\,SO_4$] density 4.5.
**barometer** 53, an instrument to measure air pressure.
**basalt** 11, *28*, *210*, a fine-grained igneous rock of basic composition.
**base level** 71, the level below which stream erosion cannot cut e.g. sea or lake level.
**basic igneous rock** *210*, with between 45% and 55% silica [$SiO_2$].
**batholith** 86, a large discordant igneous body usually of granite or gneiss.
**bauxite** 178, *206*, *213* a mineral [$Al_2O_3.2H_2O$], main aluminum ore.

**bedded** 10, term used to describe stratified rocks.
**bedding** *10*, *33*, 216, the layers in sedimentary strata.
**belemnite** *191*, a common fossil of the cephalopod class of mollusks.
**biosphere** 55, a term used to include all living things on the earth.
**biotite** 204, *206*, or dark mica, a silicate mineral [$K_2(Mg\,Fe)_2(OH)_2AlSi_3O_{10}$].



**boulder clay** *115*, a deposit formed from melting ice, also known as till.
**Brachiopoda** 128, *195*, a phylum of bivalve animals—"lamp-shells". Common fossils.
**brass** 177, an alloy of copper and zinc.
**breccia** *217*, 224, a rock composed of angular fragments.
**Brongniart,** A. 148, (1770–1847) French surveyor and geologist.
***Brontosaurus*** 134, one of the largest dinosaur reptiles.
**bronze** 175, an alloy of copper and tin.
**Brunton compass** 229, *230–1*, a geologist's pocket instrument combining compass and clinometer.
**building materials** 173
**Bryophyta** *101*, a phylum of plants; mosses.
**Bryozoa** *195*, a phylum of small moss-like animals, also called Polyzoa.

**calcareous rocks** *213*, *214*, sedimentary rocks with much Ca $CO_3$.
**calcite** 30, *200*, *206*, a common mineral [Ca $CO_3$] with many crystal forms.



—mudstone *213*, fine-grained limestone.
**calcium bicarbonate** *52*, dissolving Ca $CO_3$ in water with [$Ca(HCO_3)_2$] formed by $CO_2$.
**calcium carbonate** 32, a chemical compound [Ca $CO_3$] common as calcite.
**Cambrian** 25, *154*, the oldest geological system or period with good fossils.
**canada balsam** 215, transparent material for mounting thin sections with a standard refractive index of 1.54 when hard.
**carbonaceous rocks** *213–4*, rocks with carbon.
**carbon** *162*, 179–80, a chemical element [C].
**carbonate** 202, *206*, a chemical term used for rocks with $CaCO_3$ and $MgCO_3$ etc.
**carbon dioxide** *52*, *53*, chemical compound [$CO_2$], in air, water, and magma.
**Carboniferous** 149, *154*, a geological system or period.
**carborundum** 215, a chemical compound [SiC] nearly as hard as diamond and used as a grinding powder etc.
**carnivorous** 140, flesh-eating.
**cassiterite** 177, the mineral "tin stone" [$SnO_2$], main tin ore.
**cement** 175, mixture of limestone and clay, powdered and burnt, which sets hard after mixing with water.
**Cenozoic** 127, 135, *154*, the latest main geological era = Tertiary + Quaternary.
**centrifugal force** 59, force acting outwards owing to spin.

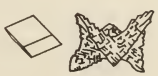
**Cephalopoda** *195*, a class of mollusks.
**chalcedony** 160, *161*, a form of silica [$SiO_2$] with no obvious crystal form.
**chalcopyrite** 177, *206*, or copper pyrites, a mineral [$CuFeS_2$], main ore of copper.

**chalk** *213*, as used on blackboard, is a form of plaster of paris [$Ca\ SO_4$]. A fine white limestone [$Ca\ CO_3$] formed of minute fossil fragments.
**Chalk** 81, a well-known formation in Britain and Europe.
**chamber** 131, space in mollusk shell e.g. living chamber.
**Chamberlin, Thomas** 20, American geologist.
**chemicals** 178
**chilled margins** 221, edge of igneous body where quick cooling has given finer grain.
**chisel** *184*, *189*
**chlorine** 179 a chemical element [Cl].
**chlorites** *206*, a group of green minerals due to alteration of other ferromagnesian minerals.
**Chordata** *195*, phylum; mainly vertebrates.
**cinnabar** *205*, a red mineral [Hg S]; main ore of mercury.
**class** *101*, 190, *195*, a technical term for a group of animals or plants, subdivided into orders.
**classification** of plants *101*
—of animals *195*
—of minerals *206*
—of rocks *210*, *213–4*
**clay** 167, *213*, a sedimentary rock; sediment with grains less than 0.002 mm.
—minerals *206*. The common minerals in clay are silicates of aluminum.
**cleavage** *89*, 174, 224, the capacity to split. Mineral cleavage is a specific property of the crystal structure; rock cleavage is of many kinds. E.g. in true cleavage the rock is split anywhere; in false cleavage it only splits in limited planes.
**climates** 113–124 (*see also* paleoclimatology).
glacial 113–122
desert 122–3
**clinometer** 230, *231*, instrument for measurement of dip or inclination.
**coal** 29, 123, *181*, *213*
—forest *80*
—mine *181*
—seam *181*
**coarse-grained rocks** *210*; a description applied especially to igneous rocks.
**Coelenterata** *195*, a phylum of invertebrate animals.
**collecting** fossils 813
—minerals 197
—rocks 209
**compass clinometer** *231*, there are many kinds, of which the Brunton is one.
**composition** of crust (all rocks) *56*
—igneous rocks *210* (chemical and mineral)
—metamorphic rocks *214*
—minerals *206*
—sedimentary rocks *213*
**compression** 91, squeezing of the earth's crust due to earth movements. The cause is not yet certain.
**concrete** 175, artificial building material made of sand, gravel and cement.
**concretion** 218, *220–2*, a natural concentration of mineral matter in a sedimentary rock, forming a distinct shape.
**cone** 82; a volcanic cone is formed of lava or agglomerate around a central vent.
**conglomerate** 212, *213*, *217*, a sedimentary rock formed of rounded pebbles or gravel.
**consolidation** 95, the process of hardening in sediments.
**contact metamorphism** 221, also known as thermal metamorphism, is due to heat of cooling igneous rock.
**continental** drift 22, *24*, *120*, the theory that continents have moved great distances relative to each other.
—shelf 56, flat part of continent beneath sea.
—slope 56, steep part of continent beneath sea.
**continents** 106
**contour plowing** *166*
**contraction** 94. Materials contract on cooling. If the earth has contracted it would explain compression in the crust.
**convection** 94, is the circulation of a fluid due to heating beneath or cooling on top. It has been suggested that circulation of the mantle (convection currents) may cause continents to move sideways.
**copper** 175 a metallic element [Cu].
—ore *206*
—pyrites *206* = chalcopyrite.
**coral** 128, *192*, *195*

—reefs *77*, 81
**core** 46, *48*, the inner part of the earth beneath the mantle.
**correlation** 137, 148, the comparison of the ages of sedimentary rocks.
**corundum** 199, a very hard mineral [$Al_2O_3$].
***Coryphodon*** 140, an archaic mammal about eight feet long.
**country rock** 12, any rock in which an igneous intrusion is found.
**crater** 82, a pit due to volcanic or meteoric explosion.
lunar 103, 107
**Cretaceous** 149, 154, a geological period or system.
**Crinoidea** 132, *132*, *195*, crinoids, or sea lilies, a class of echinoderm.
**crust** 25, *48*, *60*, outer layer of earth above mantle. Between 5 and 50 miles thick.
**cryolite** 178, a mineral [$Na_3AlF_6$]; important aluminum ore.
**crystal** 31, the typical regular form of a pure solid of which the naturally occurring kinds are known as minerals.
**crystallography** 199, study of crystals.
**crystal symmetry** is an essential part of this study. Seven systems of symmetry are recognised: cubic, trigonal, hexagonal, tetragonal, orthohombic, monoclinic, and triclinic. E.g.
hexagonal *74*, six-sided
trigonal *31*, three-sided
**Cuvier, L. C. F. D. G.** 13 (1769–1832) distinguished French paleontologist.
**cycle,** geological *97*
water
food *162*

**Dana, James D.** 18, (1813–95) American geologist and mineralogist.
**Darwin, Charles** 12, *16*, *77*, 138–9, (1809–82) English geologist and biologist, principal author of the theory of evolution by natural selection. *Origin of Species*, 1858.
**deep forces** 62, probably due to temperature changes, cause earth movements.
**Deformation** 12, refers to folding, faulting, squeezing, intrusion etc. of rocks.
**degradation** 67, or erosion, used to emphasise the lowering of the land.
**delta** 61, area of deposits at river mouth.
**density** 43, *60*, *104*, *203*, is mass per unit volume, usually compared with water of which density (or specific gravity)=1.
**denudation** 67, the effect of weathering and erosion to reduce the land.
**deposit** 17, a sedimentary rock.
**deposition** 12, 76, *97*, the forming of a sedimentary rock.
**derived fossil** 219, a fossil which has been eroded and then deposited, so it is older than the rock in which it is found.
**desert varnish** 123, *124*, the shiny surface on desert pebbles.
**devitrify** 222, for a glass to crystallize.
**Devonian** 149, *154*, a geological period or system.
**diagenic change** 89, alterations at low temperatures to sedimentary rocks.
**diamond** 156, *158–9*, 159, *206*, the hardest known mineral [C].

**diastrophism** 89–94, a general name for earth movements.
**dike** 85, *86*, *170–1*, used originally for a ditch or bank; used geologically for a thin discordant igneous intrusion which is often recognised at the surface as a ditch or bank
—swarm 92
***Dimetrodon*** 134, carnivorous Permian reptile up to 11 feet long with a great sail on its back.
**dinosaur** 134, a group of extinct reptiles dominant in the Mesozoic era and including some of the largest known.
**diorite** *204*, *210*, an igneous rock.
**dip** 230, the angle a geological surface makes with the horizontal.
***Diplodocus*** 134, one of the largest and longest of Jurassic dinosaurs.
***Dipterus*** *130*, the oldest known genus of lungfish (Devonian).
**disintegration** 64, mechanical breakdown of rocks.
**dog-tooth spar** *200*, a form of calcite.
**dolerite** *210*, a medium-grained basic igenous rock.
**dolomite** 203, *206*, a mineral [$MgCO_3$. $CaCO_3$].

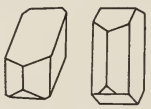


—concretion *220*
**dolostone** *213*, or magnesian limestone, a

rock rich in $MgCO_3$.
**drumlin** *113*, a form of moraine.
**dune** *68*, *119*

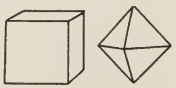
**earth evolution** 102–12
**earth movement** 49, 112, or diastrophism, the slow movements which change the earth.
**earthquake** 47, a quick earth movement due to the shock of faulting or explosions.
**earthquake waves** 49, include L-waves, P-waves, and S-waves.
**earth** sciences 35–8, *38*
—structure 40–51, *48*, *60*
weight of 43, *44*
**Echinoderma** 130, *195*, an animal phylum.
**Echinoidea** *195*, a class of echinoderms or sea urchins.
**eclogite** 62, *214*, a dense rock made of garnet and pyroxene, possibly at the top of the mantle.
**economic geology** *38*, 156–82
**elasticity** 46, property of material to spring back to original shape or volume.
**electrical survey** 236, measures the electrical resistance of rocks.
**element** 31, *206*, in chemistry is a substance consisting of one kind of atom.
**elephant** 13, *143*
**Eocene** 137, *154*, a geological period or system.
***Eohippus*** *141*, Eocene ancestor of horse.
**epeirogeny,** widespread vertical continental movements. *See* orogeny.
**epigene forces** 63, surface forces, due ultimately to energy of sun.
**equipment,** geological 183, *184*, *186*, *189*, *203*, *218*, *223*, *230–1*, *235*.
**erosion** 11, *97*, attack and removal of rock at earth's surface.
**Eurypterida** 130, an extinct order of arthropod, up to 6 feet long.
**eustatic,** change of sea level.
**evolution** 16, 138–42
—of horse *141*, 142
—of elephant 142, *143*
**evaporite** *24*, 122, *213*, a sedimentary rock due to evaporation of sea water.
**expansion** 111. Materials expand on heating and become less dense. There is a theory that the earth is expanding.
**experimental folds** *90*
**extension** 91, if the crust extends it may do so by local or globe expansion.

**family** 190; used in biological classification to group similar genera.
**fault breccia** 224; angular broken rock due to movement of fault.
**faults** *91*, 98, rock break with movement.
normal *91*, dips to downthrow side.
reverse *91*, dips to upthrow side.
strike-slip *91*, moves sideways.
dip-slip *91*, move upwards-downwards.
apparent slip, distance down fault to same bed.
heave, horizontal component of this.
throw, vertical component of this.
**fauna** 126, name for animals living at the same time and place. *See* flora *and* plants.
**felsdpar** 30, *208*, the most important group of rock-forming minerals.
—plagioclase *164*, a mixed soda-lime feldspar [$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$].



—orthoclase and microline, potash feldspars [$KAlSi_3O_8$].

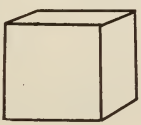
**fine-grained igneous rocks** *210*
**fissile** 217: term applied to rocks which split e.g. due to cleavage or bedding.
**fjord** *75*, Norwegian name for deep glaciated valley flooded by sea.
**flint** 117, a form of chalcedony [$SiO_2$], occurs as concretion in chalk.
**fluorite** 198, *206*, a cubic mineral [$CaF_2$].



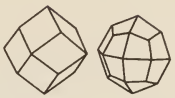
**fluvio-glacial** 76, refers to stream flowing from glaciers.
**fold** *93*, 98
anticline *92–3*
asymmetrical *93*
axis, line about which beds are folded.
isoclinal *93*
nappe *93*

overturned *93*
recumbent *93*
symmetrical *92–3*
syncline *92–3*
**fold belt** 90
**folding** 9, earth movement giving folds.
**fold mountains** 18
**food cycle** *162*, or food chain, refers to the links each organism has with what it eats and what eats it.
**Foraminifera** *78*, 137, *195*, a class of protozoa with calcareous skeletons.
**formation** 12, the making of a rock; technically a single unit of rock as used in mapping and stratigraphy.
**fossil** 9, 31–5
—ammonites *132*
—belemnite *191*
—bird *135*
—classification *101*, *195*
—collecting 183
—coral 192
—developing 188, *189*
—elephants *13*, *143*
—fern *14*
—fish *130*
—forams *78*, *79*
—graptolite *129*
—horses *141*
—identifying 190
—labelling 186
—mammoth tooth *13*
—raindrop marks *148*
—reptiles *134*, *236*
—sea-lilies *132*
—trilobite *23*
**fracturing** 9, breaking along a crack.
**freestone** 174, a sandstone or limestone easily grained and shaped.
**frost-heaving** 68, the movement of soil due to expansion of freezing water within it.
**fuels** 179
**Fusulinidae** 132, a family of large Upper Paleozoic forams.

**gabbro** 61, *210*, a coarse-grained igneous rock usually made of feldspar and augite.
**galena** 177, *206*, a cubic mineral [Pb S], main lead ore, density 7.5.



**garnet** *36*, 61, *206* group of silicate minerals [e.g. $(Ca\ Fe\ Mg)_2\ Al_2\ (SiO_4)_3$], density 3.5–4.3, formed under very high pressure.



**Gasteropoda** 135, *195*, a class of mollusks.
**genera** 190, plural of genus.
**generic name** 191, the genus name, or first of the two technical names, known as the specific name. Should be printed in *italics*.
**genus** 191, kind of group used in classifying animals and plants. A genus contains one or more species.
**geochemistry** *38*, the chemistry of minerals, rocks and the earth.
**geological age** 144–55, may be given stratigraphically or in years.
**geological cycle** 95–8, *97*, refers to interplay of deep and surface forces.
**geological hammer** 183, *184*
**geological structures** 82–94, the main subject of structural geology.
**geological time** 154
**geology** 9, 35–8, *39*, from the Greek meaning earth-science. The subject of this book.
**geomorphology** *38*, the science of land forms.
**geophone** 234, a seismic instrument for detecting vibrations of the ground.
**geophysical exploration** 233
**geophysics** 35, *38*, 40–51, the study of the earth, using physical techniques.
**geostrophic cycle** 95–8, same as geological cycle.
**geosyncline** 18, 19, 23, *60*, *112*, thick deposits usually more than 10,000 ft. of strata which depress the earth's crust into a large syncline.
**geyser** 99, intermittent fountain of hot water ejected by steam from rocks with volcanic heat.
**ghost structure** 87
***Ginkgo*** (maidenhair tree) 135, the only living representative of a large group of Mesozoic gymnosperms.
**glacial** climates 113–22
—erratic or boulder 19
**glaciated landscape** *17*, *18*, *114*
**glacier** 17, a mass of ice on land which survives from year to year.
**glass** (igneous) *210*, 222, a natural glass is formed by rapid cooling off magma or

lava, e.g. obsidian.

***Globigerina*** *78*, 137, a very small foram.

—ooze *78*, 81, *213*, made of calcareous skeletons of *Globigerina* etc.

***Glyptodon*** *16*, extinct armadillo-like mammal.

**gneiss** 90, *214*, a coarse-grained metamorphic rock usually with quartz, feldspar and dark minerals and layered or banded owing to squeezing.

**gold** 44, 59, 157, a metallic element [Au].

(native) *206*, the mineral gold occurs as an element—i.e. not in combination.

**Gondwana** 111, name for the ancient land masses of South America, Africa, India, Australia and Antarctic which have many similarities and may once have been closer together.

**goniatite** 131 ,a kind of extinct cephalopod of The Upper Paleozoic age.

**gradational processes** 63, due to sun's energy, include aggradation and degradation.

**graded bedding** 146, *147*

**Grand Canyon** *33*

**granite** 11, 24, *65*, *210* a coarse-grained rock made of feldspar, quartz and other materials e.g.:

—muscovite-biotite *208*

**granulite** *214*, 224, a fine-grained metamorphic rock mostly made of quartz and feldspar.

**graphite** 159, *206*, a soft black mineral [C] used for lead pencils etc.

**graptolite** 128, *129*, *195*, an extinct fossil.

**Graptolithina,** the phylum name for graptolites.

**gravel** *213*, sediment with grains more than 2 mm. in diameter.

**gravitation** 43, the force of attraction between masses.

**gravity** 59, the attraction of the earth

—meter 234, instrument to measure it.

—survey 59, mapping an area by gravity meter.

**Great Lakes** *117*

**greywacke** *213*, a kind of siltstone.

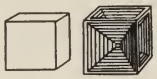
**ground-mass** 219, used for describing the part of an igneous rock between the larger crystals.

**ground water** 167, *172*

**gypsum** 122, *206*, *213*, an evaporite mineral [$CaSO_4 . 2 H_2O$] occurs as alabaster, selenite, or satin spar.

**halide** 203, *206* a compound with fluorite [F] chlorine [Cl] etc.

**halite** *206*, the mineral rock salt [NaCl].



**Hall, James** 18, (1811–98) American geologist.

**hammer** *184*, *223*

**hand specimen** *223*

**hardness** 199

**heavy spar** *206*, (*see* barite).

**heavy water** 182, [$D_2O$] occurs in water in small amounts and is useful in modern engineering.

**helium** 54, an inert gaseous element [He] formed by disintegration of radio-active elements.

**hematite** 177, *206*, *213*, a mineral [$Fe_2O_3$]. Important iron ore.

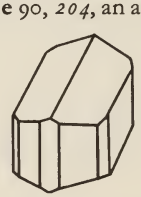
**herbivorous** 140, plant-eating organism.

**historical geology** 37, *38*, =stratigraphy.

**history of geology** 1–19, a readable book is Ruth Moore's *The Earth we live on.*

**Holland** land reclamation 170–1.

**hornblende** 90, *204*, an amphibole mineral.



**hornfels** *214*, kind of thermally metamorphosed rock, often with new minerals occurring as spots.

**horse** *141*, 142

**humus** 164, dark organic part of soil formed from decay of plants and animals.

**Hutton, James** 9, (1726–97) Scottish. One of first scientific geologists. Wrote *Theory of the Earth* (1788).

**hydrochloric acid** 179, [HCl].

**hydrogen** 55, 179, a chemical element [H].

**hydrosphere** 54, refers to all the water on the surface of the earth.

**hypogene processes** 82–94, effect of deep forces, due to thermal changes.

**hypsometric curve** *54*

**ice** age(s) 18, 113, *116*, *120*, the Quaternary ice age is the last and is sometimes known

as the Great Ice Age.
—bergs *75*
—crystals *74*
—front *117*
***Ichthyosaurus*** 133, *134*, a genus of Mesozoic swimming reptile.
**identifying fossils** 190
**igneous** 11, rock formed by solidification of magma.
—rock *65*
—rocks, classification *210*
—rocks, composition *210*
—textures *210*
**igneous intrusion,** concordant *86–7*, follows the structure (strata) of the country rock.
—discordant *86*, cuts across it.
***Iguanodon*** 134, a large Cretaceous dinosaur with massive tail and hind legs.
**impermeable rock** *172*, will not allow water to pass through.
**index fossil** 128, indicates age of rock (or conditions of formation etc.).
**intermediate igneous rock** *210*, between basic and acid, 55–65% $SiO_2$.
**intrusion** *12*, 86, *86*, the injection of one rock or magma into surrounding or country rock. Most intrusions are igneous, but salt or other soft rock may flow under pressure.
**iron** 43, *56*, 177, a metallic element [Fe].
—bearing rocks *213*
—ores 29, *206*, *213*
—pyrites *206*=pyrite
**ironstone** 177
clay *213*
oolitic *213*
**irrigation** *167*
**isostasy** 60, *60*, the natural balance achieved by segments of the earth's crust. There are various theories about this.
**isostatic movement**—vertical movement of earth's crust to changing load.
**isotope** *153*, atoms of the same element (i.e. with the same atomic number) but having different atomic weights. Most elements are mixtures of isotopes.

**jade** 162
**Jeans, James** 102, British astronomer.
**Jeffreys, Harold** 110 (b. 1891), British geophysicist and astronomer.
**joint** 217, a natural crack or fracture in rock without noticeable displacement.
—columnar jointing *28*
—exfoliation jointing=sheeting *219*
**Jurassic** 149, *154*, a geological period or system.

**Kainozoic**=Cenozoic.
**kidney iron ore** *206*=hematite.
**kyanite** *206*, a metamorphic mineral.

**L-wave** 49, in seismology.
**labeling fossils** 186
**labradorite feldspar** *164*, 199, a kind of plagioclase feldspar.
**laccolith** *86*
**lagoon** *77*
**lamellibranch**=pelecypod.
**laminated** 216, arranged in layers, especially on small scale of bedding.
**land reclamation** *170*
**Laplace, Pierre S.** 102, French mathematician.
**laterite** *213*, a red iron-rich soil typically formed in hot, wet climates.
**lava** 11, *28*, 84, *85*, magma which comes to surface in volcanic action.
**lead** 44, 177, a metallic element [Pb].
—ore *206*
**lens** *186*
**Lepidocyclina** 137, a large Tertiary foram.
**life** 25
—story of 125
**lignite** 179, a kind of peat or brown coal.
**limestone** 27, sedimentary rock rich in $CaCO_3$.
algal *213*
coral *213*
magnesian *213*=dolostone
oolitic *213*, 216
shelly *213*
**limonite** 178, *206*, a brown iron mineral [$Fe_2O_3+H_2O$].
**lithosphere** 55, the rocky crust of the earth.
**lodestone** 9, rock rich in magnetite.
**loess** 118, *213*, wind-deposited dust.
**Lyell, Charles** 12, (1797–1875), British geologist and writer of many books, especially *Principles of Geology*.

**magma** 86, *97*, subterranean hot melt, presumed origin of all igneous rock.

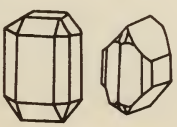
**magnesian limestone** *213*
**magnesium** *56*, a metallic element [Mg].
**magnetic north** 237, varies from true north. The magnetic poles move slowly and one is now in Arctic Canada.
**magnetism** 46
**magnetometer** 237, instrument for measuring strength of magnetic fields and developed for geophysical survey and for paleomagnetism.
**magnetite** 177, *206*, the magnetic iron mineral [$Fe_3O_4$].

**malachite** 160, *161*, a mineral [$CuCO_3$. $Cu(OH)_2$].
**mammalia** 137, *195*, a class of vertebrates.
archaic 140, extinct groups from Lower Tertiary.
**mammoth** 32, *34*
—tooth *13*
**manganese** 177, a metallic element [Mn].
**mantle** *48*, 50, *60*, the main bulk of the earth, between the crust and the core.
**map,** geological *196*, 227
paleoclimatic *120*
paleogeographic *21*, *117*, *121*
**marble** 29, *214*, a metamorphosed limestone.
**marl** 175, *213*, a soft clay-limestone.
**massive** 217, not divided by fractures such as bedding, jointing, cleavage.
**mass spectrograph** 153, apparatus for analysing isotopes.
**mass wastage** 67, denudation by wholesale movement of soil.
**meander** *70*, 171, a self-propagating river bend.
**medium-grained rocks** *210*
***Megatherium*** *15*, the giant ground sloth.
**melt stream** 76, running on glacier.
**mercury** 53, *205*, a fluid metallic element [Hg], density 13.6.
**Merostomata** 129, class of extinct arthropods.
**Mesozoic** 127, 133, *154*, a geological era ; older name was Secondary.
**metals** 175
**metamorphic rocks** 29
classification of *214*
composition of 214
**metamorphic texture** 214
**metamorphism** 88, 112, recrystallization of rocks under high pressures and temperatures.
contact- *97*
regional- *97*
**metasomatism** 88, *97*, change in composition of whole rock due to slow transfer of material.
**meteor** 44, a natural solid body from space which becomes incandescent on penetrating the atmosphere—a shooting star.
—crater *45*—due to impact of meteorite.
**meteorite** 44, *45*, a meteor which reaches the earth before being burnt up in the atmosphere.
**micas** 30, *36*, a group of silicate minerals with perfect cleavage.
white *206*=muscovite.
dark *206*=biotite.
**mica schist** 29, a metamorphosed clay or shale.
**microcline** 204, a potash feldspar.
**micro-fossil** 185, small fossil requiring special method for study.
**microscope,** petrological, i.e. polarizing, 212, *218*.
**migma** 88, *97*, an intimate mixture of melted and unmelted metamorphic rock.
**migmatisation** *97*, formation of migma by hot penetrating fluids.
**migmatite** 88, rock interpreted as a frozen migma.
**millet-seed sand** 123, well-sorted and rounded sand grains typical of desert deposits.
**Minerals** 9, 31, natural inorganic materials of definite chemical composition and physcial properties, almost always crystalline.
—classification of *206*
—collecting 197
—wealth 173–82
**mineralisation** 177, the growth of minerals of economic interest.
**mineralogy** 35, *38*, 197, study of minerals.
**miocene** 138, *154*, a geological period or system.
***Miogypsina*** 137, a Miocene foram.
**Mississippian** *154*, the lower, or older, Carboniferous period or system.
**mobile belt** 94, strip of earth's crust with continued earth movement.
**Mohorovičić discontinuity** (commonly known as the "Moho") 50, separates crust from mantle.
**Moh's scale** 199, for hardness of minerals.
**molecule** 31, the smallest particle of a

chemical substance.
**Mollusca** 128, *195*=mollusk, and invertebrate phylum.
**moon** 103
—craters 103, *107*
**moraine** 17, deposit of rock on ice and by ice.
lateral *17*, along margin of valley glacier.
medial *17*, *114*; where two glaciers meet the adjacent lateral moraines are carried down the middle as a medial moraine.
terminal *18*, *114*
**Moulton, Forest Ray** 20
**mountain building** *154*=orogenesis.
**mud cracks** 123, *146*
**muscovite** 204, *206*, *208*, white mica [$KAl_2(OH)_2(AlSi_3O_{10})$].
**mylonite** 223, rock finely ground in thrust fault.

**nappe** 91, *93*, extensive overfold and/or overthrust.
**natural classiffication** 190, one which attempts to relate things as they are related in nature.
**natural selection** 16, 139, a mechanism of evolution.
***Nautilus*** 128, a genus of cephalopod.
**nebular hypothesis** 102, of the origin of the solar system.
**Newton, Isaac** 43 (1642–1727), English mathematician.
**nickel** 45, a metallic element [Ni].
**nitrogen** 53, a gaseous element [N].
**nodule,** *see* concretion.
**North America** 98, *117*, 121, 154, 196
**nuclear** decay 82
—energy 182
**nummulite** *78*, 137

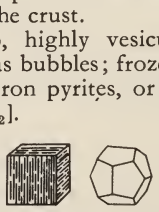
**obsidian** *226*
**oil** 178=petroleum.
—field *176*
—shale *213*
—well *176*
**Oligocene** 137, *154*, a geological period or system.
**olivine** *206*, *208*, a mineral found in basic and ultrabasic rocks.



**oolitic** 178, *216*
**opal** *165*
**opaque** minerals 199
**orbicular structure** *204*
**order** 190, used in biological classification to group similar families.
**Ordovician** *121*, *154*, a geological period or system.
**ore** 175, an economically valuable metallic mineral.
**orogenic belt** 94, strip of earth's crust with active mountain building.
**orogeny** 98, *154*, mountain building.
**orthoclase feldspar** 204
**outcrop** 227, the area on the ground where a particular rock lies exposed, or beneath the soil.
**oxbow lake** *70*, 71
**oxide** 177, *206*, a binary compound with oxygen.
**oxygen** 31, *56*, a chemical element [O].

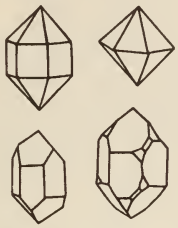
**P-waves** 49, in seismology.
**paleobotany** *38*, *101*, study of fossil plants.
**Paleocene** *154*, a geological period or system sometimes included in Eocene.
**paleoclimatology** 22, *38*, 113–24, *120*
**paleogeography** *38*, *117*, *121*, study of the past.
**paleontology** 35, *38*, 183, study of fossils.
**paleomagnetism** 237, study of "fossil" magnetism.
**Paleozoic** 127, *154*, an Era, or group of systems.
Lower 127
Upper 130
**paleozoology** *38*, study of fossil animals.
**peat** 32, accumulated deposit of dead plant material.
**pelecypoda** 133, *195*, a class of mollusk.
**peneplain** *58*, land reduced by erosion to a nearly flat surface or plain. After rejuvenation the relics of an old peneplain may still be seen in the hills.
**Pennsylvanian** *154*, the upper, or younger, Carboniferous period or system.
**period** *154*, the time during which the rocks of a geological system were deposited. Periods are grouped into Eras and subdivided into ages.
**peridotite** *210*, ultrabasic igneous rock with much olivine.
thin section *208*
**permanence** 22, the view according to which continents have remained in their

present positions through geological time.
**permeable rock** 167, *172*, allows water, etc., to pass through.
**Permian** 149, *154*, a geological period or system.
**petrogenesis** 209, the study of the ways in which rocks are formed.
**petrography** 207, the description of rocks. *See* Williams, Turner and Gilbert: *Petrography* (San Francisco).
**petroleum** *176*, 180, *213*, mineral oil.
**petrology** 35, *38*, 207, the study of rocks.
**phenocryst** 219, *224*, the larger crystals in an igneous rock where these can be distinguished from the ground mass.
**phosphorus** 55, a chemical element [P].
**photosynthesis** *162*, use of sun's energy by chlorophyll, etc., in plants to synthesise essential organic compounds.
**phyllite** *214*, intermediate between slate and mica schist.
**phylum** (plural phyla) *101*, 190, *195*, used in biological classification to group similar classes.
**physical geology** *38*. *See* Leet and Judson: *Physical Geology* (New Jersey).
**physiography** 35, *38*
**pillow lava** 222, volcanic lava formed under water and solidified in sacs.
**pitch** 32, a stiff black form of petroleum. Also used as the angle between a sloping line and a horizontal line in a dipping plane.
**pitchstone** *225*, a glassy igneous rock.
**planet** 22, *73*, *104*
**planetesimal hypothesis** 20, due to Chamberlin and Moulton in 1905.
**plankton** *78*
**plant** fossils *101*
—kingdom *101*
**plaster of paris** 185, *206* [$cCaSO_4H_2O$], obtained by heating gypsum, re-combines with water and sets hard [$CaSO_42H_2O$].
**plateau basalts** 85, extensive lava flows over continents.
**platform** 100, a stable area with flat-lying sediments, e.g. interior lowlands of U.S. *196*.
**Pleistocene** 138, *154*, the geological period, includes the Ice Age.
***Plesiosaurus*** 133, long-necked Jurassic marine reptile.
**Pliocene** 138, *154*, a geological period or system.
**plutonic** 27, deep-seated, applied to igneous rocks which are typically coarse-grained.
—processes 85, deep igneous and metamorphic.
**podsol** *169*, a kind of soil.
**polarizing microscope** 201, *218*
**polar wandering** 22, *24*, a suggested process by which north and south poles would move over the earth's surface during geological time, the axis of spin remaining constant but the earth turning slowly on other axes.
**polder** *170*
**pole,** geographical 59, axis of earth's spin at earth's surface.
—magnetic; direction in which compass needle points.
**Polyzoa** *195* = Bryozoa
**Porifera** *195*, class of animals; sponges.
**porphyritic texture** 220, applied to igneous rocks which show two sizes of crystal: phenocrysts and ground mass.
**potassium** *56*, 153, a metallic element [K].
**Poynting, J. H.** *44*, British physicist.
**Precambrian** 125, *154*, applies to all the geological time and rocks before the Cambrian system.
**precious metals and stones** 156–62.
**prismatic compass** 229, compass with dial and prism for sighting directly while reading angle.
**Proterozoic** 127, *154*
**Protozoa** 130, *195*, phylum or subkingdom of single-celled animals.
**pseudomorph** *30*, the shape of a crystal preserved in some other substance, e.g. by replacement.
***Pteranodon*** *136*, a genus of flying reptiles.
**Pteridophyta** *101*, a plant phylum.
**Pterodactyla** 134, the group (order) of flying reptiles including *Pteranodon*.
**pulsating mechanism** 111, suggested that the earth alternately expands and contracts, so leading to periodic extension and compression of the crust.
**pumice** 220, highly vesicular lava, i.e. filled with gas bubbles; frozen froth.
**pyrite** *206*, iron pyrites, or fool's gold, a mineral [$FeS_2$].



**pyroboles** *206*, joint name for pyroxene and amphibole minerals, which are often difficult to distinguish.
**pyroclastic** *41*, deposition of volcanic explosive material.
**pyroxene** 204, *206*, a group of ferromagnesian silicates.

**Quaternary** *154*, the time and rocks formed since the Tertiary; includes Pleistocene and Recent to the present day.
**quartz** 30, *36*, *206*, *208*, rock crystal, about the commonest rock-forming mineral [$SiO_2$].



—porphyry *224*, a fine-grained igneous rock with quartz and feldspar phenocrysts.
**quartzite** *208*, *214*, a sandstone with both quartz grains and quartz cement; also a metamorphosed sandstone which changes little.
**quicklime** 174 [CaO]. On heating limestone [$CaCO_3$], $CO_2$ is driven off; it reacts hotly with water to form slaked lime [$Ca(HCO_3)_2$], which then reacts with $CO_2$ to form $CaCO_3$ again—the basis of mortar.

**radiation counter** 238, instrument for measuring intensity of radioactivity.
**radioactivity** 42, natural disintegration of atomic nucleus of unstable isotopes.
**radio-dates** 153, ages in years before present, determined from rate of radioactive decay of particular elements.
***Radiolaria*** *78*, *195*
**raindrop marks** *148*
**Recent Period** *154*, 155, the latest geological period, including the present day. Some regard it as the last 10,000 years.
**reflection** 235, the turning back at a surface of waves of light, or sound, or earthquake waves. A technique in seismic survey.
**refraction** 236, the change of direction when the above waves pass from one medium to another. A technique in seismic survey.
**rejuvenation** *58*, 72, the effect on a landscape of increased erosive energy imparted to a stream by uplift, reduced sea level, etc.
**Reptilia** 131, *134*, *136*, 140, *195*, a class of vertebrates.
**reservoir rock** 168, *176*, 180, a porous rock which contains oil or water.
**revolution** 98, 112, used for a period of mountain building resulting in a change of geography.
**rhyolite** *210*, 223, *224*, *225*, a fine-grained acid igneous rock.
**ripples** *68*
**ripple marks** *68*, *145*
**river terraces,** paired *69*. Unpaired river terraces are formed by gradual downcutting of a meandering stream.
**rock** 9, 27–31
—crystal *206*
—cycle 95
—drilling bits *235*
—salt 29=halite.
—structures and textures 216
**rock**—classification *210*, *213–14*
—collecting 209
study of 207=petrology.
**ruby** 160, a red variety of corundum [$Al_2O_3$].
**run-off** 163, running water in streams, etc., which does not sink into the ground or evaporate.

**S-wave** 49, in seismology, depends on rigidity of transmitting medium.
**salt crystals** *30*
**salt domes** 150, *151*
**salt in the sea** 150
**salts** *213*
**sand, sandstone** 27, *213*, sediment with grains between 0.02 and 2.0 mm. in diameter.
**sapphire** 160, blue or other colored variety of corundum [$Al_2O_3$] except red.
**satellite** 53, *104*, bodies rotating round planets, e.g. the moon round the earth.
**scale model** *90*, may have the correct geometrical scale and be made of any materials. It may also be scaled in time, and move. If the forces are scaled the strengths of materials must be carefully chosen.
**schist** *36*, 90, *204*, *214*, a metamorphic rock with parallel growth of platy or rod-like minerals.
calc- *214*
garnet-mica- *214*
graphite- *214*
mica- *214*

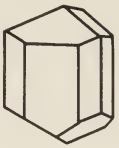
**Schmidt, Otto** 102, Soviet astronomer.
**sea lilies** *195*=crinoids.
**sea urchins** 133, *195*=echinoids.
**sediment** 9, material carried in and deposited from air, water or ice.
**sedimentary** 9, implies relatively low temperature and pressure conditions of formation.
—rocks, classification of *213*
—rocks, composition of *213*
**sedimentation** 76
**seismic survey** 234, a geophysical method of investigating the sub-surface structure using artificial explosions and recording the shock waves as they are reflected or refracted back to the surface.
**seismogram** 49, *51*, record of seismograph.
**seismograph** *47*, instrument for recording earthquake waves.
**seismology** 47–50, study of earthquakes and especially earthquake waves.
**septarian concretion** 218, *222*
**septum** 131, the dividing wall between two chambers in a fossil.
**serpentine** *37*, *206*, a group of ferro-magnesian minerals related to chlorite and formed by alteration of olivine. Also commonly used for a rock with much serpentine in it due to alteration of a peridotite, etc.
**shale** 27, *213*, a fissile sedimentary rock of clay composition.
**sheeting,** *219*, a kind of jointing.
**sial** *60*, from silicon [Si] and aluminium [Al], used for upper part of earth's crust in which these elements predominate.
**siderite** *206*, an iron mineral [$FeCO_3$].
**silica** 32 [$SiO_2$] used for the material whether as a separate compound or in combination with others.
—content *210*
**silicates** 203, *206*, group of minerals containing essential silica; most important rock-forming minerals.
**siliceous rocks** *213*, *214*, with silica [$SiO_2$].
**silicon** 31, *56*, a chemical element [Si].
**sill** 85, *87*, a thin concordant igneous intrusion.
**silt, siltstone** *213*, 217, sediment with diameters of grains between .002 and .02 mm.
**Silurian** *154*, a geological period or system.
**silver** 156 a metallic element [Ag]; the mineral silver occurs as an element as well as in combination.
native *206*
**sima** *60*, from silicon [Si] and magnesium [Mg], the dominant elements in that part of the earth below the sial. Probably includes the lower crust and upper mantle.
**skeleton** 32, the hard part of an animal or plant (e.g. shell) which is usually the part preserved as a fossil.
**slate** 27, *89*, *214*, a fissile rock used for roofing. The best slates are well cleaved rocks of clay composition.
**slaty cleavage** 224, the best example of true cleavage, in which minute flat minerals gains were all perpendicular to some major compression. The rock splits along this direction.
**slickenside** 224, grooves or scratches in rock due to earth movement.
**slide** *91*, a great sheet of rock moved over other rocks in mountain building—a kind of nappe.
**slumping** 217, sliding of newly formed sediments down sub-aqueous deposition slope.
**Smith William** 14, (1769–1839), an English engineer, "father of historical geology".
**snowflakes** *74*
**soapstone** *37*, soft rock with talc.
**sodium** *56*, a metallic element [Na].
**soil** 163
—auger 229
—conservation *166*
—profile *169*
**solar** energy 182, due to nuclear transformation and transmitted to earth as electromagnetic radiation, where it heats the atmosphere, etc., and works the "surface forces".
—system 20, *73*, *104*
**solid geology** 228, the geology of an area, ignoring the Quaternary deposits.
**solifluxion** 68, the moving of soil usually due to water and freezing.
**source rock** 180, where petroleum is formed. It may be found there or migrate to a reservoir rock.
**species** 35, the natural biological unit in classification which contains all varieties of organism of the same kind. An interbreeding population.
**specific gravity** 201, density in relation to water=1.
**specific name** 191, in two words is usually made up from Latin and Greek and written in *italics*; it consists of a generic plus a trivial name.
**Spermophyta** *101*, a plant phylum.

**sphalerite** 177, *206*, or zinc blende, a mineral [ZnS]. Main zinc ore.

**spherulite** 222, a spherical growth of radiating crystals in a glassy igneous rock.
**spherulitic** texture *225*
—granophyre *225*
**sponges** 130, 195, =Porifera.
**spring** (of water) *168*, 169, a natural outlet of ground water.
**squeeze box** *90*
**stage** 149, used in stratigraphy for a unit smaller than a system. Consists of several zones.
**stalactite** 29, *52*
**stalagmite** 29, *52*, *65*
**starfish** *195*
***Stegosaurus*** 134, a dinosaur with armoured plate along spine.
**stony-iron meteorite** 45
**stoping** 87, a mining term for undercutting. The method of intrusion of an igneous rock by swallowing up blocks of country rock which sink into magma.
**storing specimens** 189
**strata** 29, *10*, *33*
**stratification** 216
**stratigraphy** 35, *38*, 98–100, 125–55
**streak** 198, the distinctive color of a powdered mineral.
**strike** 230, the direction of a horizontal line in a geological surface.
**Stromatoporoidea** *195*, extinct coral-like organisms.
**structural geology** 35, *38*, the study of rock structures, especially the geometry and mechanics of rock deformation.
**structure contours** 229, strike lines at known heights above sea level.
**structures,** geological 82–94
rock 216, 223
**submarine canyon** 79, steep gorge beneath sea—origin uncertain. Possibly eroded or kept clean by turbidity currents.
**subsidence** (see also uplift) *97*
**sub-surface exploration** 232
**sulphate** *206*, a chemical group [$R_2SO_4$].
**sulphide** 177, *206*, a chemical group [$R_2S$].
**sulphur** 179, *206*, a chemical element [S].
**sulphuric acid** 179, an important economic product [$H_2SO_4$].
**superposition,** law of 144, earlier sedimentary rocks are normally overlain by later ones unless disturbed afterwards, *see* way-up evidence.
**surface exploration** 229
**surface forces** 62, due to solar energy through atmospheric circulation.
**surface wave** (L-wave) 49, in seismology.
**syenite** *210*
**symmetry** *see* crystal, *see* fold.
**syncline** 19, *92–3*, a downward fold.
**system** 148, *154*, a group of rocks formed during a geological period and capable of international correlation. Systems are subdivided into stages and then zones.

**talc** *36*, 199, a soft metamorphic mineral [$Mg_3Si_4O_{10}(OH)_2$].
**talus** *66*
**tectonic transport** 93, transport of rock by earth movement, *see* denudation and deposition.
**temperature of earth** 40–2
**Tertiary** *154*, the main part of the Cenozoic Era.
**texture** 216, 223, minute structure
—of igneous rocks *210*
metamorphic rock *214*
schistose *214*
gneissose *214*
granulose *214*
maculose *214*
**Thallophyta** *101*, a plant kingdom.
**theodolite** 60, instrument for surveying angles accurately.
**thermal metamorphism** 221, due to temperature.
**thin section** *204*, *208*, 215, *224–6*
**thorium** 42, a radio-active element [Th].
**throw** (*see* fault)
**thrust** 98, a dip-slip reverse fault.
**thrust mass** 91, rocks overthrust some distance.
**tidal theory** 102, of origin of solar system advanced by Jeans and modified by Jeffreys.
**tide** 46. The sun and moon attract the waters on the earth and to a lesser extent distort the earth itself.
**till** 114, *115*, *213*, boulder clay, a deposit from ice.
**tillite** *24*, 114, *115*, *120*, *213*, a consolidated till.
**tilting** 10, of parts of the earth's crust can

be measured by accurate leveling. Epeirogenic movements involve uplift and subsidence with tilting.
**time-scale** 144–55
**tin** 175, a metallic element [Sn].
**Topaz** 199, a mineral [$Al_2SiO_4(F,OH)_2$].
**tourmaline** *201*, *206*, schorl, a metamorphic mineral, a complex silicate with Na, Ca, Mg, Fe, Al, B, and F.



**trace-fossil** 34, *39*, the fossilized trace of an organism's movements, etc., e.g. footprints, from which the mode of life may be inferred.
**trachyte** *210*
**transport** 61, *97*
**tree rings** 123
**Triassic** 149, *154*, a geological period or system.
**trigonal** 31, *see* crystal symmetry.
**trilobite** *23*, 129, 195, an extinct arthropod, important fossil in Lower Paleozoic.
**trimming a specimen** 223
**trivial name** 191, the second part of a specific name.
**tuff** 83, *213*, a consolidated volcanic ash or dust.
**turbidity current** 79, moves under water when a disturbance fills a body of water with sediment, which having greater density flows down any slope at some speed.
***Tyrannosaurus*** 134, a large cretaceous dinosaur with powerful teeth and minute fore-legs.
***Vintatherium*** 140, a large Eocene archaic mammal with curious knobs on the skull.

**ultrabasic** *210*, igneous rock with less than 45% silica.
**unconformity** 9, *11*, a stratigraphical break with some angle between the earlier and later rocks. A small unconformity identified by missing zones is a nonsequence and by a change of lithology as a disconformity.
**uniformitarianism** 16, a view originated by Hutton, developed by Lyell, and generally accepted today that the past can be interpreted in terms of present-day processes.
**uplift** 61, *97*
**uranium** 42, a radio-active element [U].

**varve** *147*, 217, a clay with graded bedding due to seasonal melting ice.
**ventifact** 123, *124*, a wind-facetted pebble.
**vermilion** *204*
**Vertebrata** 128, *195*, main part of phylum Chordata.
**vesicle** *84*, *85*, 160, a gas cavity in a lava.
**vesicular texture** 220, of lava.
**volatiles** *97*, materials which are lost from magma and may migrate through rock.
**volcanic** 27
—ash 83
—bomb *84*
—cone *41*
—crater *84*
—lava 11, *84*, *85*
—neck *83*
—vent *41*
**volcano** 11, *41*, 82
**Vinci, Leonardo da** 13, (1452–1519) Italian painter, sculptor, engineer, and architect, who made important scientific contributions.

**Wallace, Alfred Russell** 138 (1823–1913), British architect and traveler.
**water** 53, 163 [$H_2O$].
connate *55*
—cycle 54, *55*
ground 167, *172*
juvenile *55*
meteoric *55*
—supply 167–72
**waterfall** *62*
**water table** 167, *168*, 172, the free upper surface of water saturating a rock.
**waves,** *see* earthquake.
**way-up evidence** 144, *145–8*, evidence as to whether sedimentary rocks have been overturned. *See* superposition.
**weathering** 63, the chemical decomposition and mechanical disintegration of rock due to the atmosphere, rain, soil, etc.
**Wegener, Alfred** *24*, 111, author of *Origin of Continents and Oceans*, etc., developing the theory of continental drift.
**wind-polished pebble** *124*, ventifact.
**wrench fault** 98, a kind of strike-slip fault.

**xenolith** *12*, 221, a piece of country rock isolated in an igneous rock.

**zinc** 177, a metallic element [Zn].
—blende *206*, =sphalerite.

**zircon** 152, a mineral [Zn $SiO_4$] found as minute crystals in granites.

**zone** 94, 149, a group of strata characterised by a definite assemblage of fossils.
**zone fossil** 128

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